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A combined catchment and reach-based assessment of historical
channel planform change in a UK upland gravel-bed river

Duncan Wishart

Thesis submitted for the degree of Doctor of Philosophy

Department of Geography
University of Durham

2004

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Abstract

River channel planform change in upland gravel-bed rivers has consequences for riparian land use, river habitats and flood hazards. Channel planform is predominantly determined by the balance between sediment supply and prevailing discharge regime which is governed by climate and land use, and anthropogenic channel modification. While the nature of channel response to individual factors is in some cases well documented, the complex interaction of these variables and their relative significance requires further evaluation. This study assesses the nature and extent of historic (1856-1991) channel planform change in the upland catchment of the River Wear, Northern England. A nested research strategy is adopted consisting of catchment wide and reach-scale evaluations of channel planform change using archival maps and aerial photographs. The cause of channel changes is considered with reference to hydrological records (1800-present), catchment land use (metal mining) and accounts of river channel modification (gravel extraction). Comparative historic (reach-scale) and contemporary (trunk channel) data is provided from the upper reaches of the River Tees in Teesdale, Northern England.

In the mid nineteenth century a pulse of sedimentation migrated through the upper Wear catchment resulting in the development of eight major sedimentation zones with channel braiding separated by confined single thread reaches. Increased sedimentation was related to a combination of high magnitude floods during the nineteenth century and enhanced sediment supply from extensive metal mining in tributary streams. A decline in flood frequency and magnitude coupled with the cessation of metal mining during the early twentieth century, led to a reduction of sediment supply and lateral channel instability in the catchment. This promoted gravel bar stabilisation through vegetation colonisation, reducing average channel width by 56%. In the sedimentation zones, gravel bar extent declined by up to 87% and this was accompanied by a change to a single thread planform. Gravel extraction operations during the mid-twentieth century lead to local instability and delayed the decline in gravel bar area. In contrast the contemporary channel of the upper Tees is still characterised by localised channel division, around both active gravel bars and vegetated islands. Differences between the two catchments demonstrate the importance of catchment specific controls such as bedrock control and anthropogenic channel interference. A large flood on 30 July 2002 provided significant insight into the mechanism of channel planform change. Substantial increases in gravel bar extents were recorded together with localised changes in flow routing. While local controls such as gravel extraction are significant over decadal time scales, catchment scale controls, primarily changes in the frequency of large floods, determine channel planform over centennial timescales. In order to discriminate between local and catchment controls, catchment wide assessments are required.

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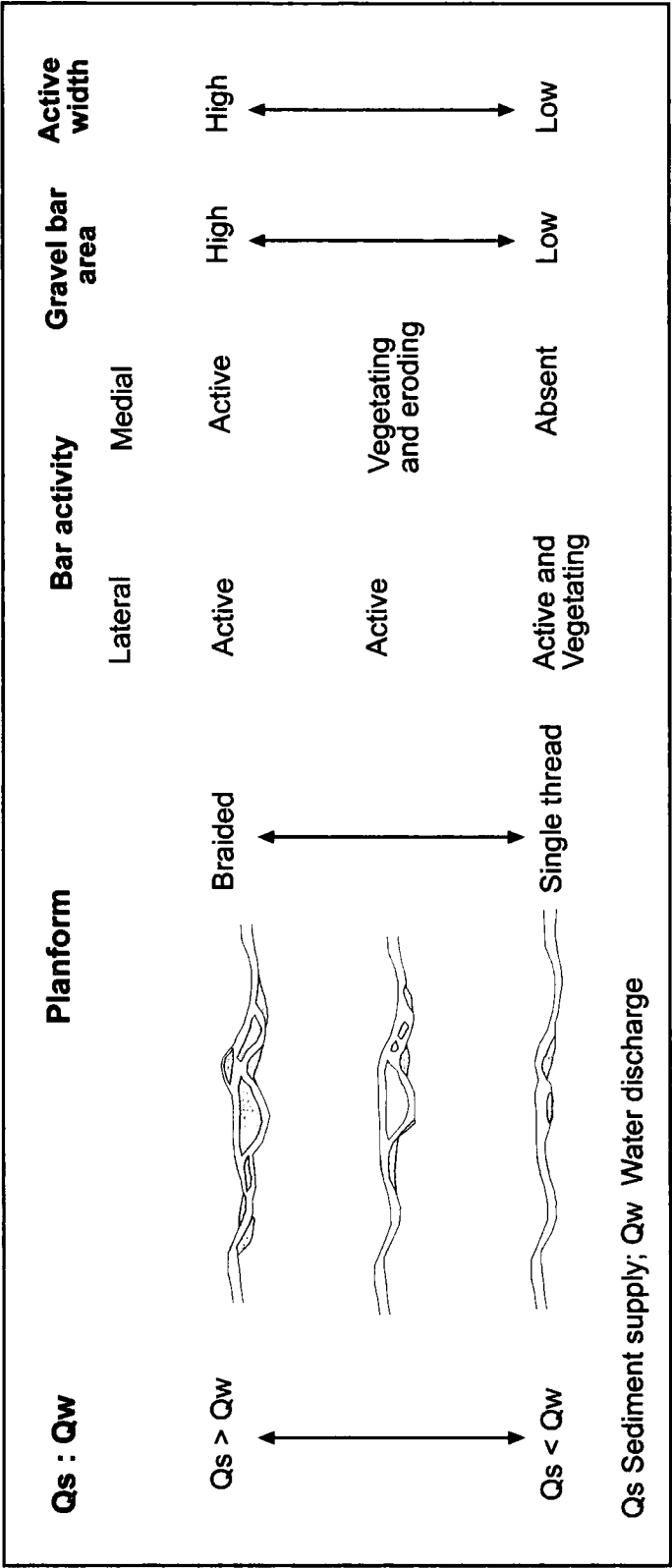
Chapter 1 Introduction

1.1 River channel planform change in upland catchments

Upland river channels are of considerable geomorphological importance. Their relatively steep gradients, high sediment availability, erodible banks, flashy regimes and high stream power, make them susceptible to planform change. It is estimated that 35% of British upland channels have been subject to some degree of channel change between 1870 and 1959, from relatively minor bend changes to reach-scale planform metamorphosis (Hooke and Redmond, 1989a). Planform change in such rivers creates significant difficulties for landowners because sedimentation can reduce channel capacity, leading to both increased flooding and higher bank erosion rates. This in turn results in loss of valuable farmland and structural damage to property and bridges. Understanding the causes of channel planform change is important given the prospect of future climatic change, which may alter river behaviour through increases in flood frequency and magnitude.

Upland river channels consist mainly of gravel-beds with local bedrock control. In such rivers the quantity and rate of coarse sediment supply is a key control on channel planform (Fuller et al., 2002). Variations in the quantity of sediment supplied to the channel, relative to dominant discharge, leads to changes in channel planform (Figure 1.1 and Table 1.1). Where the channel is not laterally confined, high sediment supply leads to the development of extensive gravel bars, in particular the formation of mid-channel bars (Harvey, 1991) (Figure 1.2). Under such circumstances the channel becomes laterally unstable, leading to increases in bank erosion (Figure 1.3), which promotes further growth in gravel bars. Conversely, a decline in the rate of sediment delivery leads to a reduction in the extent of gravel bars, and the channel becomes less laterally extensive and contains fewer gravel bars (Figure 1.1). The planform of upland rivers therefore provides a general indication of the rate of sediment delivery to the river channel. Variations in channel planform within a catchment reveal information concerning the spatial variability of sediment delivery in catchments, while changes in channel planform over time allow the temporal changes in sediment supply to be determined. Laterally unstable braided channel planforms were common in British upland rivers during the nineteenth century (Passmore et al., 1993) but during the twentieth century these channels changed

Figure 1.1 Conceptual model of channel planform response to changes in sediment supply and discharge regime.



to a single thread planform with a substantial decline in the extent of active gravel bars (Brewer et al., 2000). Understanding the cause of variations in coarse sediment delivery to upland channels and the nature of its transfer through a catchment enables the origin of recorded channel planform change to be evaluated.

Table 1.1 Channel changes in response to changes in water and sediment leading to river metamorphosis (modified from Schumm, 1977).

Change	River bed morphology	Planform tendency
$Q_s + Q_w =$	Aggradation - channel instability, wider and shallower channel	Braided
$Q_s - Q_w =$	Incision - channel instability, narrower and deeper channel	Single thread
$Q_w + Q_s =$	Incision, channel instability, wider and deeper channel	Single thread
$Q_w - Q_s =$	Aggradation, channel instability, narrower and shallower channel	Braided
$Q_s + Q_w -$	Aggradation	Braided
$Q_s + Q_w +$	Processes increased in intensity	No change
$Q_s - Q_w -$	Process decreased in intensity	No change
$Q_s - Q_w +$	Incision, channel instability, deeper, wider? channel	Single thread

Key: Q_s sediment discharge; Q_w Water discharge; + increase, - decrease, = no change, ? uncertain response

Figure 1.2 Localised channel braiding on Trout Beck in the upper catchment of the River Tees, flow is from right to left. High rates of bank erosion are occurring along the left bank in response to mid-channel bar deposition.



Figure 1.3 Bank undermining due to bar deposition along Trout Beck, upper Teesdale.



Variations in the balance between sediment supply and discharge regime in upland channels is affected by a range of factors. These include climatically driven variations in flood frequency and magnitude (McEwen, 1994; Milne, 1982; Rumbsey and Macklin, 1994; Werritty and Leys, 2001; Winterbottom, 2000), low frequency high magnitude storm floods (Carling, 1986a,b; Ballantyne and Whittington, 1999), slope-channel coupling (Harvey, 1991; Harvey, 2001), land use such as metal mining (Lewin et al., 1983; Macklin and Lewin, 1989), over grazing (Harvey and Renwick, 1987), ditching for forestry (Newson, 1980b) and agricultural land drainage (Longfield and Macklin, 1999). Increasingly, however, emphasis is placed on studying the combined influence of these processes in recognition of their complex interaction within upland catchments (Macklin, 1986a; Macklin et al., 1998; Warburton et al., 2002). In order to determine the impact of these changes on the channel network their geomorphological impact must be determined (Table 1.2).

In addition to the range of climatic and catchment land use factors identified above, direct anthropogenic modification of river channels can also lead to changes in river channel planform, either directly or through changes in sediment supply (Table 1.2).

Channel changes due to reservoir impoundment (Petts, 1979), gravel extraction (Sear and Archer, 1998), channelization (Brookes, 1987; Leeks et al., 1988) and flood embankment construction and abandonment (Parsons and Gilvear, 2002) have been recognised throughout Britain particularly over the last 50 years. To date, however, the wider significance of these processes and their interaction with climatic and land use changes in the British uplands remains unclear. For example the coincidence of these influences with the decline in channel braiding since the early 20th century requires further evaluation.

Table 1.2 The range of factors that may influence sediment delivery and discharge in upland channels (modified from Rumbsy, 2001, p.92).

	Sediment delivery	Discharge
<i>Climatic influences</i>		
Meridional circulation	+/-	+ Major floods
Intermediate circulation	-	Fewer floods
Zonal circulation	+	+ Moderate floods
Random convective storm events	+	+
<i>Catchment land use</i>		
Forest clearance	+	+
Afforestation	+	-
Intensification of agricultural activity (grazing, arable)	+	+
Land drainage	+	+
Mining activities	+	+
<i>Direct channel and floodplain modification</i>		
Flood embankments	-	+
Dams and reservoirs (flow regulation)	-	+/-
Removal of river bank trees	+	
Channelization	+/-	+
Sand and gravel extraction	-/+	

Geomorphological conditioning can also play an important role in the propensity of a channel to undergo change. For example the degree of confinement determines the degree to which the channel can migrate. The frequency of contacts between the channel and slopes composed of unconsolidated sediments can influence the rate of sediment supply (Harvey, 2001). In addition, variations in the channel gradient throughout a catchment can have significant impact on channel planform (Warburton et al., 2002). Determination of the importance of geomorphological influences on

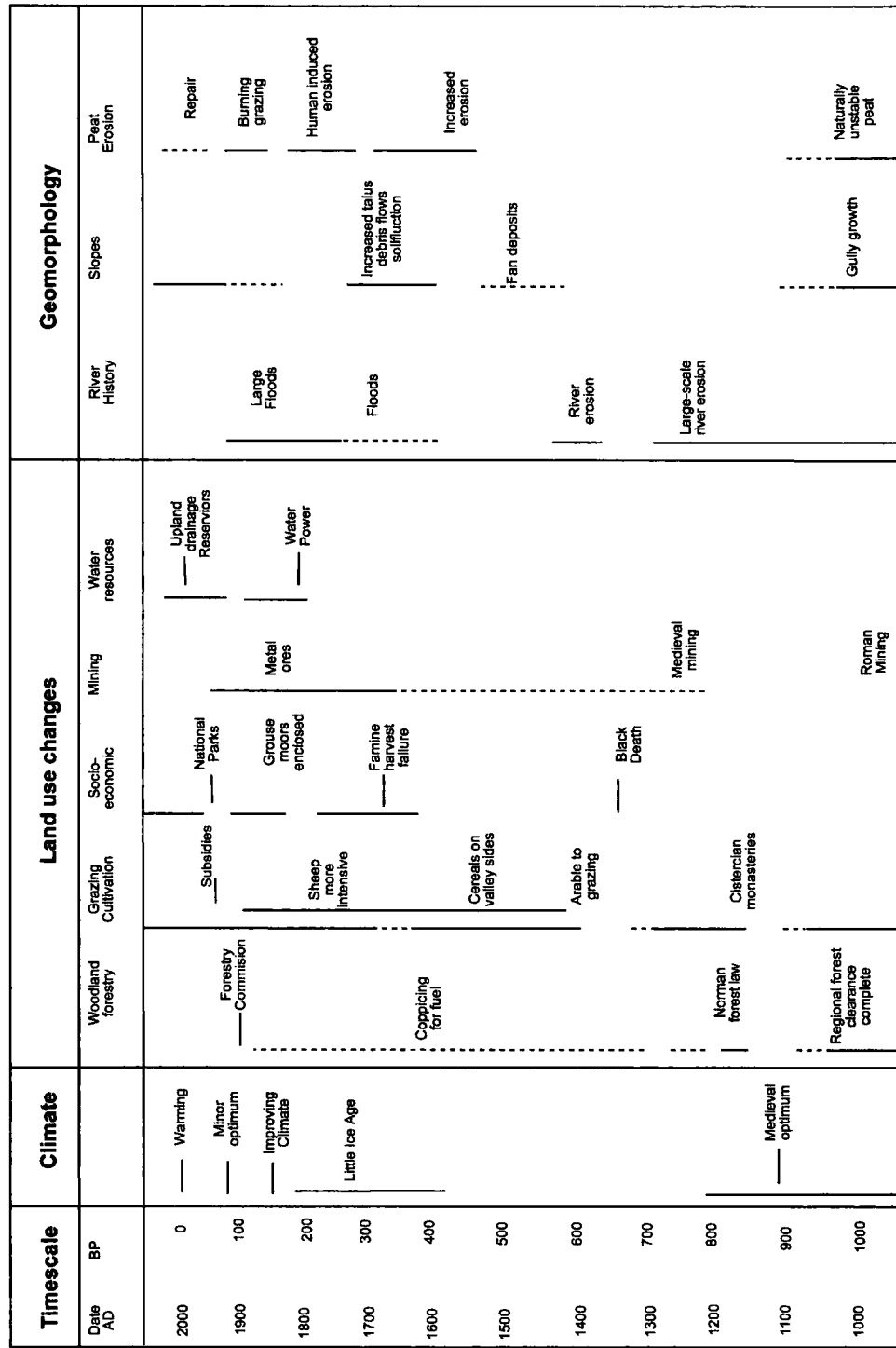
channel planform has been relatively neglected in British upland catchments, with the exception of low order channels with frequent slope-channel contacts (Harvey, 1985).

Over the last thousand years the extent to which these processes have influenced the geomorphology of upland catchments has varied and the last 150 years has been a time of particularly pronounced change in the uplands of Northern Britain (Figure 1.4). An understanding of the way in which river channels behaved over the last 150 years is central to determining the future stability of river channels, as climate and land use change (Newson and Lewin, 1991). Studying this period provides the opportunity to determine channel response to a wide range of influences. In addition, determining river channel behaviour over historic time enables long-term trends in channel to be defined (Kondolf, 1994). Contemporary problems such as flooding, sedimentation and bank erosion are likely to have been influenced by climate, land use and direct channel modifications of the last 150 years. When considering strategies to mitigate problems such as these, it is essential to understand the longer-term geomorphological context of the channel (Gilvear, 1999).

Historical analysis of channel behaviour enables the temporal scale of a problem to be identified, aiding the interpretation of cause and the selection of appropriate management strategies. Historical investigations into planform change benefit from the availability of historic maps and aerial photographs spanning the last 150 years (Hooke and Redmond, 1989a). These enable direct channel planform reconstructions to be produced, as opposed to indirect reconstructions of planform behaviour offered by sediment sequences. Reliable map and aerial photograph evidence also provides an indication of the role of geomorphological influences, such as the frequency of slope-channel contacts. The availability of land use and flood records for the last 150 years enable historical studies to consider the response of fluvial systems to extrinsic variables. Archival records of channel interference are also available for the last 150 years and provide a further level of detail, which is desirable for a holistic understanding of planform change.

Despite the range of processes operating over historical time and the range of data sources available, few attempts have been made to assess the influence of the full range of process interactions on channel planform change throughout a catchment. The lack of a comprehensive appraisal of process interactions can be related to the reliance of many studies on reach-scale investigations. A common

Figure 1.4 Schematic chronology of landscape change in the uplands of northern England over the last 1000 years. From Higgitt *et al.*, 2001.



strategy has been to select one or more (seldom more than three) reaches to be examined in a given study. Reaches selected are often those which appear to have an interesting geomorphological history. This raises questions about the representativeness of the field sites. Where the representativeness of the reach cannot be adequately established, reach-based work may bias our understanding of the significance of processes in the wider context of the catchment or region. This is particularly significant when a limited range of processes is under consideration.

Regional appraisals of channel behaviour are therefore desirable (Macklin, 1999) and represent an important area of recent research development (Brewer et al., 2000; Macklin et al., 1998). The catchment of the River Tyne, Northern England, for example, is one of the most extensively studied catchments in Britain. Many reaches have been investigated in the upland section of the catchment, most notably the South Tyne catchment (Figure 1.5). Research over the last two decades has allowed an understanding of channel behaviour throughout this upland catchment to be developed. The intensity of research in the South Tyne catchment is almost unique, yet the range of planform controls considered in detail is relatively limited. Studies were designed to investigate the influence of metal mining (Aspinall and Macklin, 1985; Macklin and Lewin, 1989), long-term flood frequency trends (Macklin et al., 1992a,b; Macklin et al., 1994; Rumsby and Macklin, 1994) or combinations of both (Aspinall et al., 1986; Macklin, 1986a; Macklin et al., 1998; Passmore and Macklin, 2000), on channel behaviour within the catchment. As part of these studies, speculations concerning the significance of other processes such as slope channel coupling (Macklin and Lewin, 1989), flood embankments (Passmore et al., 1993) and gravel extraction (Macklin et al., 1998) have been made. However, the nature of their impact was not fully quantified, particularly in a wider context.

In order to improve our understanding of the causes of planform change in upland catchments, several key questions remain to be addressed:

- How does the pattern of sediment generation and transfer vary throughout upland catchments and how does this influence channel planform?
- To what extent are channel changes in reaches biased by local controls and how representative are they of the catchment as a whole?
- How does flooding and land use interaction vary throughout a catchment?
- How significant is catchment geomorphology, such as valley slope and channel confinement?

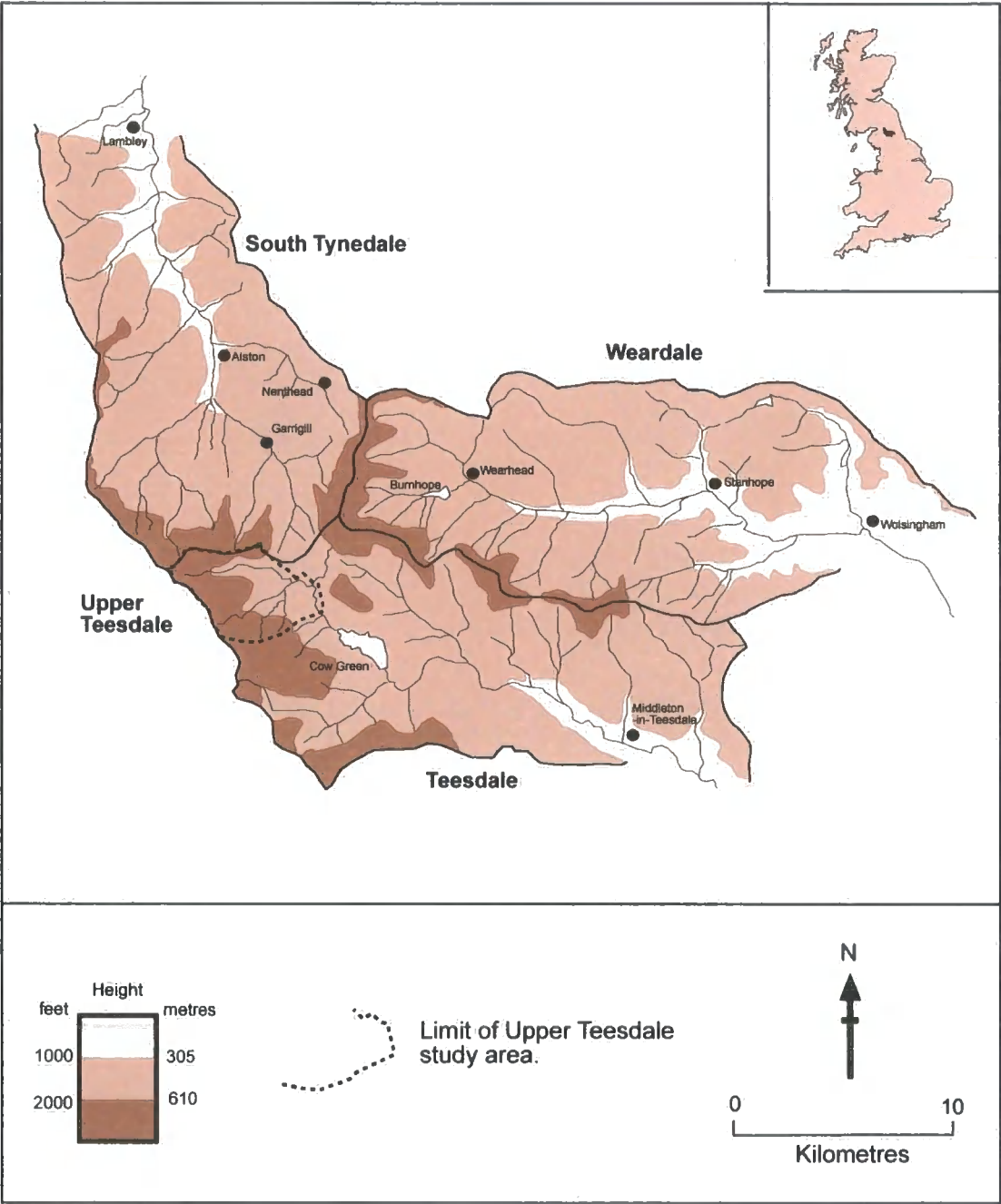
- How important are anthropogenic channel modifications such as gravel extraction?
- How representative is one catchment of others in that region?

1.2 Research strategy

In order to assess the relative importance of a range of planform controls a combined catchment and reach-scale approach was adopted. The majority of the research focuses on the upland catchment of the River Wear in Weardale, County Durham (Figure 1.5). Located in the North Pennines this catchment provides an upland setting comparable to that of the neighbouring South Tyne, which has been extensively studied (Macklin, 1997b). The investigations in Weardale focused on channel activity over the last 150 years, a period of change in the British uplands (Higgitt et al., 2001) for which a range of historic sources is available. The investigation adopted a nested research strategy (elaborated upon in Chapter 3), the first phase of which involved a catchment scale assessment of historic sedimentation patterns and channel planform changes. Change in the distribution and extent of sedimentation within the catchment were determined by mapping changes in gravel bar extents over last 150 years, within a GIS framework. The associated changes in channel planform change were then classified and their locations incorporated into the GIS. This allowed the impact of catchment-wide influences such as climate and land use to be assessed. Nested within this, contiguous channel width series measurements were recorded along the trunk channel of the catchment, as this appeared to be representative of changes occurring throughout the catchment. This also enables channel planform changes to be quantified for selected time intervals during the last 150 years. Finally, spatially distributed reach scale investigations were undertaken, enabling detailed planform changes to be reconstructed and the impact of localised controls to be determined.

A second study was undertaken in the upper catchment of the River Tees in upper Teesdale (Figure 1.5). This catchment was selected because it exhibits contemporary channel division, has experienced a similar land use and flood history to the River Wear (and Tyne) but is located at a greater altitude and has contrasting catchment morphology (stepped long profile). Investigations here consisted of the

Figure 1.5 Map showing the location of Weardale and upper Teesdale in relation to South Tynedale.



measurement of contemporary channel width structure along a study reach incorporating the trunk channel of the catchment, which could be compared directly to the Weardale data. Nested within this, reach scale reconstructions of historic channel planform change were produced for selected sites along the study reach. Finally the impact of a high magnitude flood event (30th July 2002) on channel planform structure was investigated in relation to channel planform changes along the study reach.

The wide range of potential controlling mechanisms, from climate to metal mining, to channelisation and alluvial gravel extraction provide an excellent opportunity to assess the importance of a wide range of controls. Additionally the investigations conducted within these two catchments encompass a range of upland channel settings, with varying degrees of lateral confinement, bedrock control and channel gradients (0.02-0.004). This is significant as it enables the role of geomorphological setting to be elucidated. Their proximity to other catchments, which have been studied in a similar context, most notably the South Tyne (Figure 1.5), reinforces the rationale for site selection.

1.3 Aim and objectives

The aim of this thesis is to undertake a combined catchment scale and reach scale appraisal of planform change throughout two upland catchments (including both trunk channel and tributary streams) in order to determine the main processes controlling the observed planform changes. A key aspect is the determination of the relative importance of these controls. The thesis focuses specifically on the historic period (the last 150 years), a period of particularly pronounced change in the uplands (Figure 1.4). This timescale also enables the research to benefit from a range of archival sources, such as maps, aerial photographs and land use records. To this end the specific objectives of the thesis are:

1. Provide a catchment wide assessment of changes in gravel bar extents and the incidence and extent of channel planform change in Weardale over the past 150 years, using archival sources.

2. To quantify changes in channel planform width structure along 31 km of the River Wear (the trunk channel of the Weardale catchment) between 1856 and 1991.
3. Produce detailed reach-scale reconstructions of channel planform change between 1856 (locally 1844) and 1991 at sites where significant planform change has been identified in Weardale. This allows the extent of reach-specific controls to be identified.
4. Measure the contemporary channel structure of the trunk channel of the Upper Teesdale catchment (River Tees and Trout Beck) and provide reach scale channel planform reconstructions for sites with evidence of historic channel planform change. This will enable the wider significance of the findings from Weardale to be established and help to determine the importance of catchment geomorphology.
5. Quantify changes in channel planform produced by high magnitude flood events with reference to the flood of 31 July 2002 in upper Teesdale. Recorded channel changes will be compared to those determined from the historical records to determine the importance of low frequency high magnitude flood events.

The study aims to determine the extent to which planform change may be controlled by catchment-scale factors such as flood frequency and magnitude as opposed to localised influences such as geomorphology and anthropogenic activities.

1.4 Thesis Structure

This thesis begins with a review of the existing research into river channel planform changes in upland catchments. The nature of planform changes identified in previous studies is summarised. Of particular significance are the differing spatial and temporal scales adopted by workers and the need to move towards a nested combination of reach-scale research within a whole catchment assessment. Extrinsic and intrinsic mechanisms thought to cause planform change are discussed. A conceptual model detailing river channel response to both intrinsic and extrinsic processes is developed.

Chapter 3 evaluates the range of differing methodologies used to identify planform change and determine likely causal mechanisms. The broad methodological framework adopted in this thesis is outlined and justified in light of the literature review. The detailed methods adopted are then described. The catchment scale (regional) appraisal of the incidence of planform change in Weardale is outlined and the development of GIS-based mapping discussed. The use of historical sources to reconstruct historic reach-scale planform change histories is explained, with particular reference to data capture and GIS manipulation. The sub-catchment scale research undertaken in upper Teesdale is then presented and the combination of fieldwork and historical map analysis is defined. Finally the field sites, Weardale and Teesdale are described in detail and the rationale for their selection is justified.

Chapter 4 outlines the results of the catchment-scale assessment of the distribution and extent of planform change. A series of GIS maps which classify the distribution of changes in sedimentation over the periods 1856-1896, 1896-1919, 1919-1951 and 1951-1991, are presented. An additional GIS map summarising the nature of associated historic channel planform changes within the catchment is also included. Summary graphs derived from the GIS to aid the interpretation of these maps are also included. The timing and spatial patterns of sedimentation are then related to catchment-scale controlling mechanisms, specifically variations in flood frequency and magnitude, and metal mining.

Chapter 5 compares measurements of channel width derived at 50 metre downstream intervals along the River Wear (the trunk channel of Weardale) for the years 1856, 1896, 1951 and 1991. These results help to quantify the distribution of sedimentation within the catchment and enable changes in the extent of gravel bars to be determined. The changes in channel width over time are then considered in terms of the potential controls discussed in chapter 4.

Chapter 6 examines channel reaches in Weardale characterised by planform change over the historic period. Series of sequential channel planform diagrams form the core of this chapter. Data derived from these diagrams include changes in gravel bar areas and channel sinuosity. These examples enable the influence of catchment-scale processes identified in chapter 4 to be discussed in terms of reach-scale adjustments, and also allow reach-specific controls to be identified. The impacts of mid-nineteenth century railway construction and late 20th century gravel extraction

from the River Wear at Wolsingham and Harperley Park provide illustrations of the importance of reach-specific influences.

Chapter 7 examines the relationship between catchment geomorphology and historic planform change in upper Teesdale. Detailed measurements of channel width structure were made at 20 metre intervals along 6 km of the catchment trunk channel. The downstream variation in planform is related both to local controls such as gradient, and is also compared to the historical channel width data from Weardale. Detailed channel planform reconstructions are provided for reaches identified as exhibiting a history of planform change. The significance of high magnitude, low frequency storm events are examined in relation to the impact of a large flood event on the 31 July 2002 along Trout Beck. The channel planform changes caused by this flood are then compared to historic channel planform changes in the catchment to determine the significance of such events over historic time scales.

Chapter 8 compares the findings of the research in Weardale and upper Teesdale to the studies summarised in chapter 2. Comparing the response of differing catchments to similar forcing mechanisms is a key theme explored here. The extent to which catchment-scale and reach-specific mechanisms can be disentangled represents the crux of the chapter. The chapter concludes by considering the implications of future climatic and land use change and likely channel response, as well as the implications of the research for the future management of upland catchments, with particular emphasis on managing river channel change.

Finally chapter 9 provides a summary of the work undertaken, presents the conclusions of the research and gives suggestions for further research.

Chapter 2 The nature and cause of river channel planform change in UK upland catchments

2.1 Scope of chapter

This chapter reviews the styles and causes of river channel planform change in British upland catchments. It begins by establishing the nature and mechanisms of historic channel planform changes recorded in the British uplands over the historic period. Having determined the processes of channel planform change, the chapter considers the causes of planform change. This section examines a range of influences including climatic controls, catchment land use, direct anthropogenic channel modification, and geomorphological controls. These processes influence channel planform by altering the discharge regime and the quantity and rate of sediment delivery to the channel. The downstream propagation of changes in the balance between water and sediment discharge is highlighted as this provides the key control on channel response within the catchment. Finally the chapter reflects on the complexity caused by the interaction of factors that determine discharge and sediment supply regimes. The chapter concludes by considering the challenge of attempting to determine the relative importance of processes.

2.2 The nature of planform change in British upland catchments

2.2.1 Channel planform classification

Channel planform in gravel-bed rivers is classified according to the distribution of gravel bars (Bridge, 2003). A series of planform typologies have been identified to aid the interpretation of process influences (Richards, 1986), although it is important to recognise that these planform typologies lie within a continuum of forms (Leopold and Wolman, 1957) (Figure 2.1). Channel planform classification is determined by a combination of three criteria:

- (i) Sinuosity; ratio of channel distance (thalweg) to valley length.
- (ii) Braided index; number of bars and islands per meander wavelength
- (iii) Lateral stability of the channel(s)

--(Brierley, 1996, p263)

Figure 2.1 Classification of channel planform, within the morphological continuum, modified from Brierley (1996, p 270).

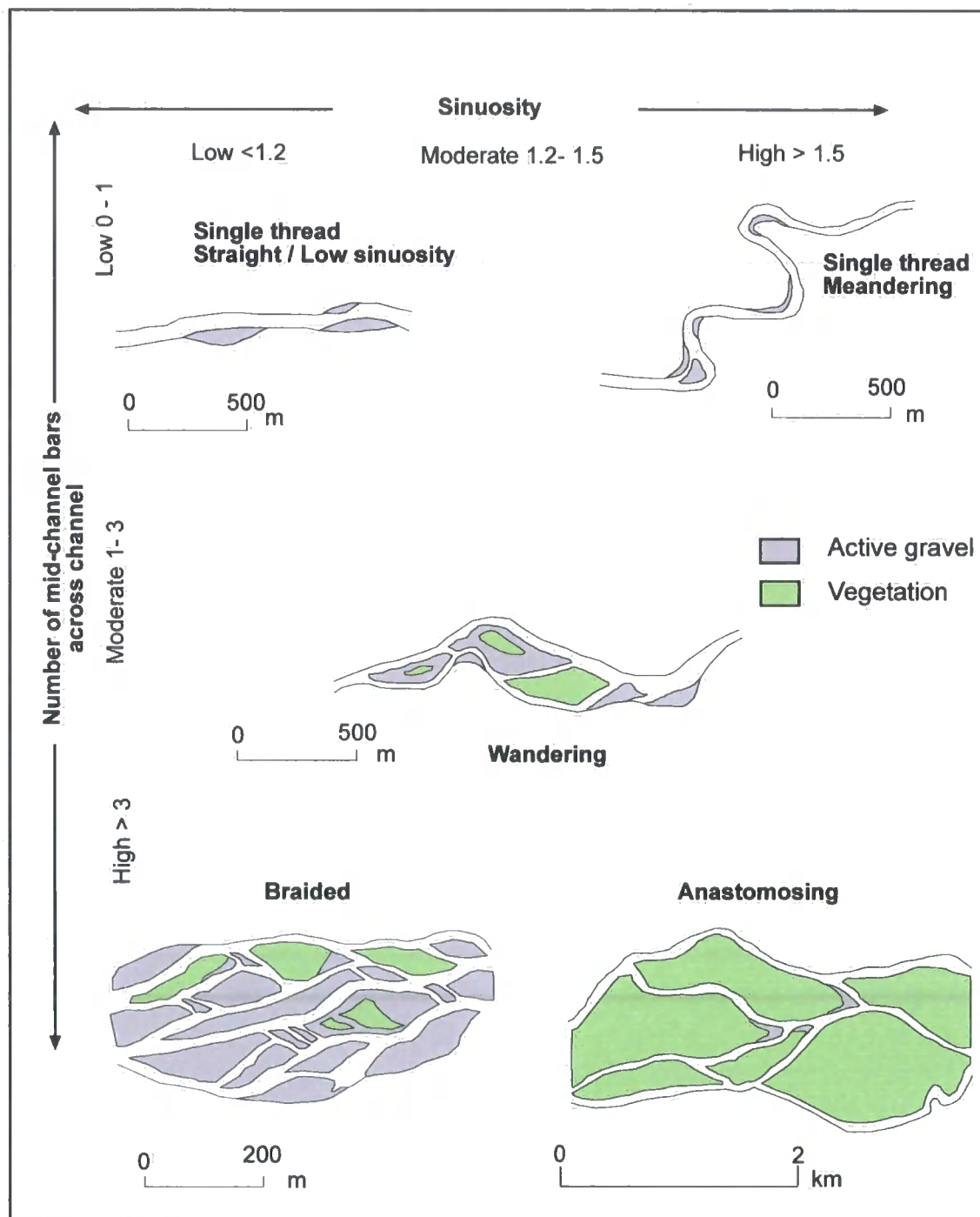


Figure 2.1 places commonly cited channel planform typologies within the context of the continuum of form. Within this scheme the most important channel planform attribute is the distinction between single thread channels (straight and meandering) and multiple thread channels (braided and anastomosing) (Bridge, 2003). Single thread channels are characterised by the presence of lateral gravel-bars with only a few isolated mid-channel bars, whereas braided channels are those where mid-channel bars are numerous, resulting in flow division and convergence (Bristow and Best, 1993). In many gravel-bed rivers, however, channel division occurs within discrete zones (sedimentation zones) separated by intervening single thread reaches. Such channels are described as exhibiting a wandering planform (Church, 1983). In the context of British gravel bed-rivers the most important distinction lies between single thread channels and wandering channels. Multiple thread channels are particularly important, as they are dynamic with frequent changes in bar organisation. They are laterally unstable which can lead to loss of surrounding land.

2.2.2 The process of planform change

Planform change in gravel-bed rivers occurs in a variety of forms and at a variety of spatial and temporal scales (Figure 2.2). Planform changes within a planform typology are common and have been widely recognised, for example: bend evolution and associated bar development (Passmore et al., 1993), gravel bar reorganisation in near braided (wandering) gravel-bed channels (Passmore and Macklin, 2000) and changes in braided river planform (Ferguson and Werritty, 1983; Lewin and Weir, 1977; Werritty and Ferguson, 1980). However the transformation from one planform typology to another (channel metamorphosis) is of the greater importance as this represents a fundamental shift in the behaviour of the river channel. Such changes include both temporary channel transformation from one type to another such as from sinuous to near straight and partly braided and back to sinuous (Warburton and Danks, 1998), or complete metamorphosis from single thread to braided (Harvey, 1991). In the Pennines and Welsh uplands planform change frequently involved localised changes from single-thread to braided channels during the nineteenth century and the development of a single-thread planform during the twentieth century (Macklin, 1997b). Elsewhere channel braiding has been associated with large floods through changes in sediment supply (Harvey, 1991). Figure 2.3 provides selected examples of such historic planform changes.

Figure 2.2 Classification of channel planform change styles in gravel-bed rivers

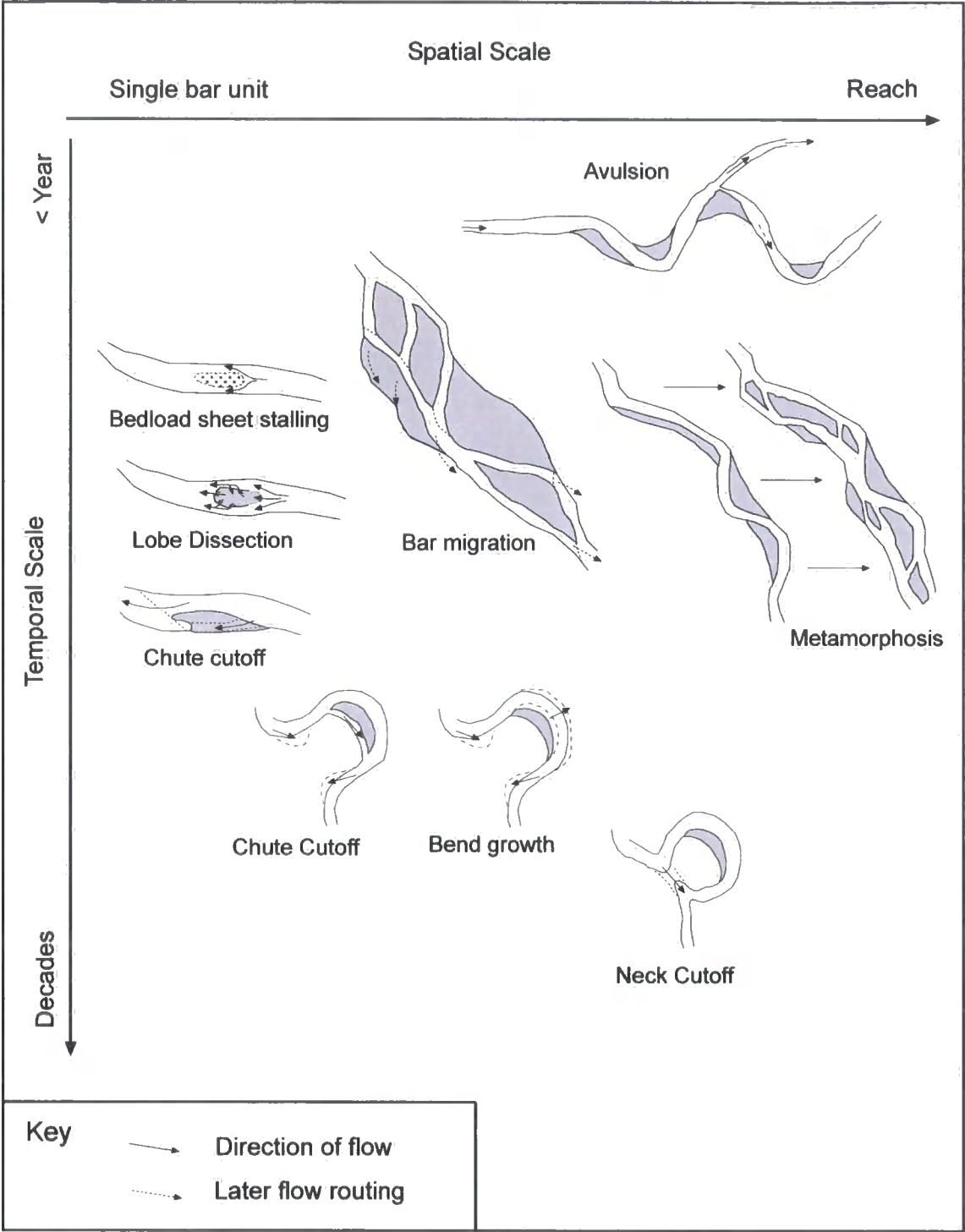
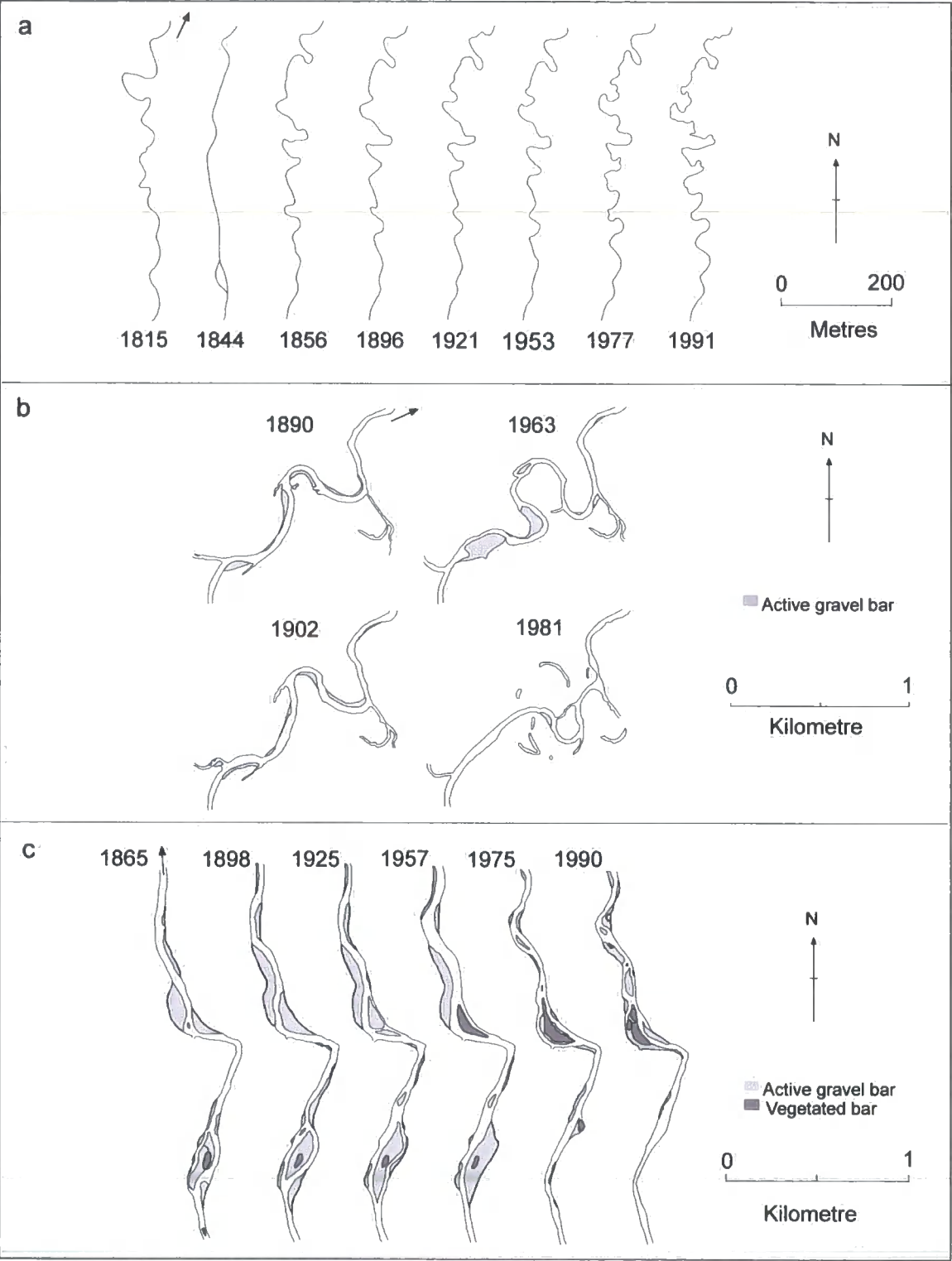


Figure 2.3 Examples of historic channel planform change from British gravel-bed rivers: (a) transformation from high sinuosity to low sinuosity and back (Warburton and Danks 1998 p87), (b) bar and bend evolution (cutoff) (Passmore et al., 1993 p217) , (c) bar adjustment in a wandering gravel-bed river sedimentation zone (Passmore and Macklin, 2000 p1247) . Flow directions indicated by arrows.



The transformation from a single thread channel to a braided channel may be initiated by a number of mechanisms, either by erosion or deposition (Ferguson, 1993). In the British uplands, channel braiding with multiple mid-channel bars are associated with sedimentation zones (Passmore and Macklin, 2000; Passmore et al., 1993). Within these reaches deposition is the dominant mechanism of channel braiding. In detail, several mechanisms have been suggested to account for the development of mid-channel bars through sedimentation on the bed of rivers (Figure 2.2). Bed load sheet stalling can form the nucleus of a gravel bar which forms through sediment accretion (Leopold and Wolman, 1957). A similar mechanism is transverse bar conversion, where sheets of bed load stall on the surface of bed lobes downstream from scour pools. Continued deposition eventually promotes the emergence of the lobe and the formation of a single mid-channel bar, flow is then diverted around either side (Ashmore, 1991b). An alternative suggestion is that emergent lobes may be dissected in multiple locations thus creating a series of mid-channel bars (Church and Jones, 1982) (Figure 2.2). Mid-channel bars may also form via erosional mechanisms. Chute cut-off may convert lateral bars into mid-channel bars (Ashmore, 1991b) (Figure 2.2). Here headward incision from the front of a diagonal riffle (of which the bar is a component) occurs during high flow events. This process, while erosional, is favoured by growth of the lateral bar both through deposition extending the extent of the bar across the channel and increasing the height of the bar. This mechanism of channel change was observed in the River Feshie, a wandering gravel bed river (Ferguson and Werritty, 1983).

In braided rivers and sedimentation zones of wandering gravel-bed rivers multiple lateral and mid-channel bars occur. Here, diagonal bar (riffle) migration can be an important mechanism for the re-routing of channel flow (Ferguson and Werritty, 1983). Riffle migration alters the point at which flow impinges on riverbanks, and where this coincides with topographic lows, channel avulsion is likely. Channel avulsion is an important mechanism of channel change within braided gravel-bed rivers, but it may also occur in single thread channels where sediment deposition may constrict the channel and lead to out of channel flow (Warburton et al., 2002). Channel avulsion is likely to be initiated in such settings by flood events (Werritty and Leys, 2001). Here a completely new river course can be excavated. The channel planform typology of the river can be transformed by avulsion, typically through the initiation of channel braiding (Werritty, 1997a). However over longer time scales the channel may recover as the new channel captures all the flow, or the original channel

recovers as the sediment constriction is removed and flow is diverted along the original course.

The development of a single thread channel from a previously braided planform was widespread during the nineteenth century (Europe) and twentieth century (British uplands). This change is essentially an erosive response to decreased sediment load particularly during flood events when the flow has an excess of energy. Additionally it may be encouraged by channelization techniques, which confine flow to a narrow zone during flood events and promote erosion of the bed rather than the banks. In locations where the channel is not laterally confined, single thread channels may develop a meandering planform (McEwen, 1997). This is encouraged by progressive erosion whilst bar deposition encourages meander development (Lewin, 1976). Ultimately however, bends grow too large and are cut-off (Passmore et al., 1993) (Figure 2.3). Two styles of cut-off are commonly referred to, these are neck cut-off typically occurring at the neck of the bend and chute cut-off (Hooke, 1987; Hooke and Redmond, 1989a) (Figure 2.2). Bend cut-off can lead to localised sedimentation as the channel re-establishes equilibrium, leading to flow division (Fuller et al., 2003b). In gravel-bed channels, chute cut-offs tend to be more common than breaches across a narrow neck (Figure 2.2) (Lewis and Lewin, 1983).

2.3 Processes leading to planform change in the British uplands

As mentioned in chapter 1, channel planform is primarily controlled by the balance between the mean discharge of water and sediment (Schumm and Lichty, 1965). In order to determine the cause of changes in channel planform it is necessary to establish the factors that govern water discharge and sediment delivery. A range of factors have been identified which can induce channel change, through modification of the discharge regime of the catchment, or through the quantity and rate of sediment delivery to the channel. In addition, direct anthropogenic modifications to river channels can be important causes of planform change, and the nature of channel planform changes produced by these influences is also controlled by the structure of the catchment (geomorphological conditioning).

2.3.1 Climatic influences

Climate can drive upland geomorphological processes in various ways. On a regional scale, changes in weather circulation patterns can produce changes in the flood

frequency and magnitude experienced by catchments. Locally, high magnitude low frequency storm events can significantly alter channel planform over a short time period (hours). However the extent to which the occurrence of these are controlled by decadal climatic variations is uncertain. At the scale of individual bedrock and sediment exposures, periods of wetter climate and/or increases in length and severity of winter frost processes can increase the quantity of sediment transferred from the slope to river channel.

2.3.1.1 Atmospheric circulation

The frequency and magnitude of flooding in British upland catchments can be related to different patterns of northern hemisphere climatic circulation. Climate in the northern hemisphere alternates between phases of meridional and zonal circulation patterns (Lamb, 1977). This appears to be controlled by the temperature gradient between equator and the poles (Lamb, 1982). Warmer conditions in the middle and lower latitudes induce west to east circulation of the circum polar vortex through low amplitude widely space waves, termed zonal circulation (Rumsby and Macklin, 1994). Cooler periods increase the lateral temperature gradient and this favours north-south and easterly wind patterns (meridional circulation), this is associated with the southward displacement of the main air streams that have a higher wave amplitude and frequency (Rumsby and Macklin, 1994). Cooler meridional periods lead to low evapotranspiration rate and increased likelihood of snow, and consequently melt induced runoff, both of which make large floods more likely (Rumsby and Macklin, 1994). Intervening phases with no dominant circulation pattern are termed intermediate periods. The timing of the dominant climate circulation types affecting Britain has been established for the last 200 years (Table 2.1).

Table 2.1 Alternation of dominant climate circulation type (based on Rumsby and Macklin, 1994).

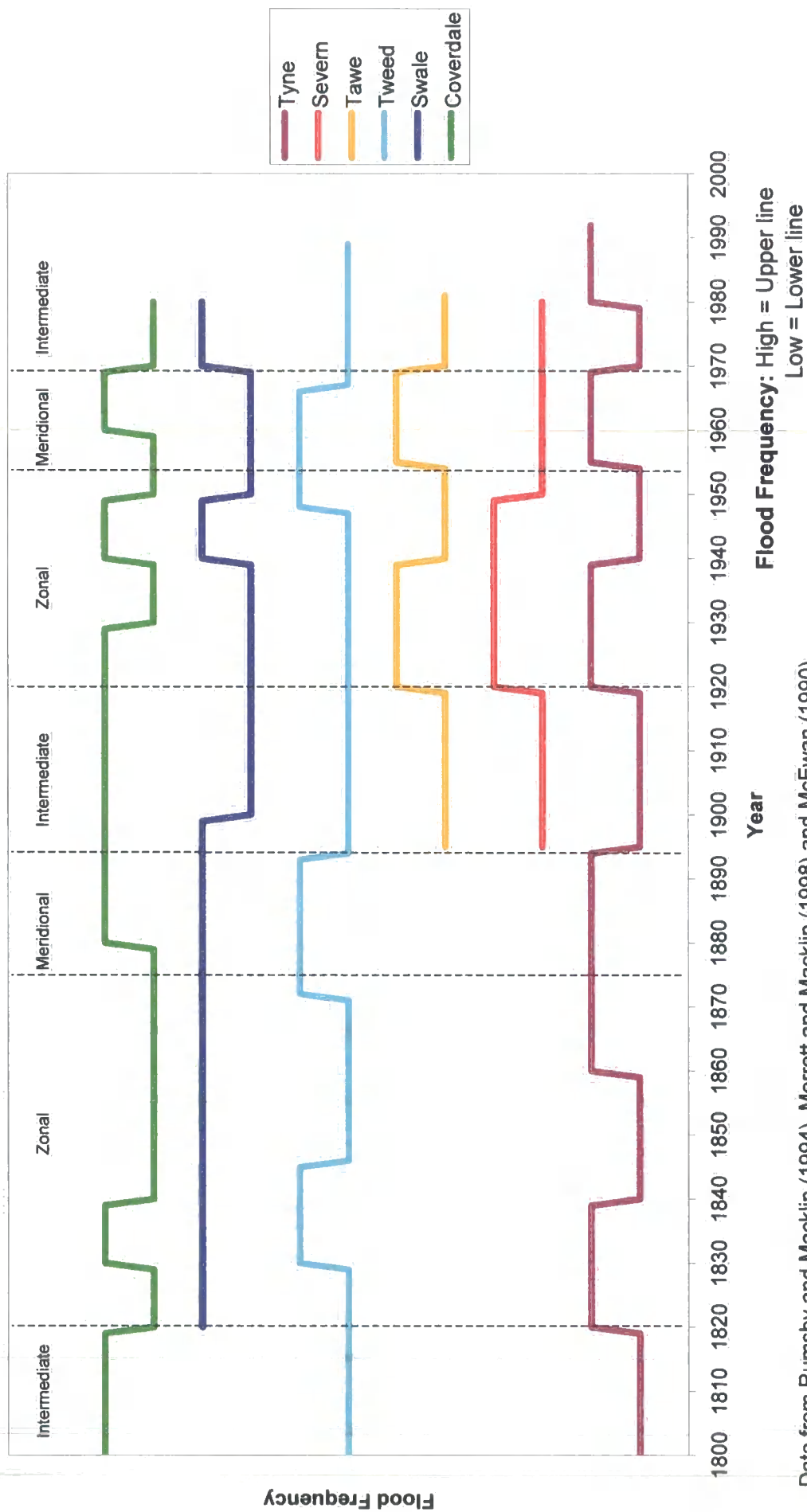
Dates	Dominant circulation pattern
1800-1819	Intermediate
1820-1874	Zonal
1875-1894	Meridional
1895-1919	Intermediate
1919-1954	Zonal
1955-1969	Meridional
1970-1979	Intermediate
1979-present	No dominant pattern

Alternations in atmospheric circulation were found to coincide with changes in flood frequency and magnitude in the Tyne basin. Meridional periods lead to an increase in the frequency of major (>20 year return period) floods while an increase in the occurrence of moderate (5-20 year return period) floods occurs during zonal periods. Intermediate phases however, are characterised by low flood frequency and magnitude and result in limited channel activity (Rumsby and Macklin, 1994). However, the relationship between river flooding and climatic circulation is spatially variable.

The incidence of phases of increased and decreased flood frequency and magnitude for six British catchments are compared in relation to alternations in climatic circulation identified by Rumsby and Macklin (1994) (Figure 2.4). This diagram illustrates the variation in the timing and direction of flood frequency changes for each catchment. Despite the variations in the length of available records a number of important similarities and contrasts can be discerned. The Tweed and Tyne records are very similar and this is likely to be due to their proximity and comparable setting, while the largest floods on the River Severn occur during zonal climate phases, which may be linked to its westerly location (Rumsby and Macklin, 1994). The location of this catchment may also explain the decline in flood frequency during the meridional phase of the mid-twentieth century. Basins draining to the north or east of rainfall divides are likely to experience increased flood frequency and magnitude during enhanced, meridional circulation, whereas basins draining to the south and west of rainfall divides should experience increased flood frequencies during zonal periods (Rumsby and Macklin, 1996).

The Swale and Coverdale catchments in the Yorkshire Dales appear to respond to climate circulation differently (Merrett and Macklin, 1999). Coverdale responds in a similar manner to the Tyne and Tweed, although intermediate circulation is also associated with high flood frequencies. The response of the Swale however, is significantly different to the other catchments. Zonal circulation patterns seem to be more significant causes of flooding than meridional. Changes in flood frequency do not appear to correspond simply to changes between zonal and meridional. The Swale and Coverdale flood frequency data is based on dated flood deposits (Merrett and Macklin, 1998) rather than documented records and this may bias the results because the distinction between high and low flood frequency is based on relatively few floods. Also the deposition of flood deposits is dependant on sediment availability in addition to flood magnitude, and this can bias the flood record.

Figure 2.4 Flood Frequency for six British Catchments 1800-2000.



Data from Rumsby and Macklin (1994), Merrett and Macklin (1998) and McEwan (1990).

Comparing the flood records for Coverdale and the Swale must be done with caution. Coverdale is a headwater stream, a tributary of the River Ure, and has a very small catchment in comparison to the Swale. Rumsby and Macklin (1994) argue that archive flood records, used to reconstruct flood histories for entire upland catchments, are likely to underestimate flooding in headwater streams. The extent to which flood events in headwater streams may represent flooding the wider catchment is difficult to assess, particularly as small catchments can be susceptible to anthropogenic activities such as drainage ditching, which can alter flood frequencies (section 2.3.2.3). In addition, reconstructing long term flood records in headwater catchments using flood deposits risks confusing long-term climatic circulation effects with convective storm events that may be independent of climate circulation (discussed in the following section). Yet in the context of channel planform change, flood reconstruction utilising flood deposits can be beneficial as these indicate floods that have a significant impact on the fluvial system. This is useful in upland catchments that may not have complete archival flood information (Macklin et al., 1994). The record of floods indicated by deposits in the landscape is, however, dependant on the sequence of flood events. The occurrence of large floods may remove geomorphological evidence of earlier floods of a low magnitude, and flood events with close temporal proximity may not be discernable using landform evidence.

Climate can have a range of geomorphological impacts and this can result in a lack of uniformity of river channel response within a basin. A phase of channel incision in upland tributaries of the River South Tyne occurred during the phase of increased flood frequency and magnitude associated with the culmination of the Little Ice Age (Macklin et al., 1992a). Sediment released by incision was augmented by material released from rock shattering and slope instability due to increased freeze-thaw activity (Rumsby and Macklin, 1996). Similarity reduced evapo-transpiration and a wetter climate destabilised slopes through higher pore water pressures increasing the frequency of landslides (Grove, 1985) further increasing the delivery of sediment to river channels. In the trunk channel however, the resulting increase in sediment delivery caused aggradation and the onset of channel braiding (Passmore et al., 1993).

The increased frequency of moderate flood events, associated with periods of zonal climate circulation in the Tyne catchment, resulted in sediment release from the upper reaches of the catchment which was then transferred downstream and

deposited in the trunk channel (Rumsby and Macklin, 1994). In contrast to this relatively local sediment transfer, the frequent high magnitude floods of meridional climate phases tend to result in channel incision along both the tributaries and trunk channel (Newson, 2003). For example during the late nineteenth century episodes of riverbed incision occurred in both trunk channels and tributary streams in the upper reaches on the South Tyne (Rumsby and Macklin, 1994). However local variations in channel response occurred in response to catchment land use. Channel aggradation in the upper reaches of the South Tyne during the late nineteenth and early twentieth century was promoted by sediment release from metal mining (Macklin and Lewin, 1989; Passmore et al., 1993; Macklin, 1997c). In addition the geomorphological structure of the channel network also results in variations in channel response. Reaches with pronounced lateral confinement tend to experience incision; as the magnitude and frequency of flooding increases, the sediment released is then deposited laterally in unconfined reaches.

In contrast to the nineteenth century, the phase of meridional circulation during the mid-twentieth century in the South Tyne was characterised by widespread channel incision, extending to the whole of the upland catchment, including sedimentation zones (Passmore et al., 1993; Rumsby and Macklin, 1994). This phase of channel incision coincided with a reduction in active gravel area in the sedimentation zones, as opposed to the increases in gravel area recorded during the high flood frequency period of the early nineteenth century. However, the magnitude of channel changes during the twentieth century has also been linked to land use activities in the catchment; primarily the cessation of metal mining, an increase in land drainage and gravel extraction (Macklin, 1997b). Clearly channel response to flood frequency and magnitude is strongly influenced by additional processes, the impact of which is discussed in the following sections.

Insight into the significance of other processes driving planform change has been provided by a review of the relationship between planform and flood frequency in Scotland (Werritty and Leys, 2001). This review considers the impact of flooding simply in terms of "flood-rich" and "flood-poor" periods (Werritty and Leys, 2001). Historic planform change in Scottish rivers was of a lower magnitude than that in either the Tyne or Severn catchments. River channel response to flood frequency has taken the form of lateral shifts rather than the vertical and lateral changes recorded in the Tyne and Severn catchments. Flood rich periods are associated with high rates of lateral floodplain reworking, while flood poor episodes have low rates.

Significant planform changes were restricted to large flood events and involved channel straightening during the flood, followed by renewed bend growth in the years after. Large floods were also linked to channel avulsion in a number of instances, but this is not regarded as being particularly significant because it does not involve floodplain reworking. The only recorded case of channel metamorphosis, the River Coiltie, is accounted for by an increase in local base level due to the increase in level of Loch Ness (Werritty and Leys, 2001).

The examples from Scotland discussed by Werritty and Leys (2001) raise an important question. Fundamentally what constitutes significant planform change? Lateral shifts of up to $10\text{m}^2\text{m}^{-1}\text{yr}^{-1}$ and channel avulsions are not regarded as significant planform in this context, yet in the North Pennines of England such changes would be highly significant (Warburton et al., 2002). What constitutes significant planform change depends upon the history of the river channel. Those channels subject to high rates of lateral migration (Feshie and Derry Burn) and avulsion (Coiltie and Ey Burn) have a history of frequent shifts from single thread to braided channels following high magnitude floods. These channels are termed 'wandering gravel bed rivers' (Werritty and Ferguson, 1980) and are clearly adjusted to dynamic flood regimes. These rivers are considered to be behaving in a robust manner, that is, changes in flood frequency do not alter the overall wandering channel planform (Werritty and Leys, 2001).

In English and Welsh rivers transformation from a sinuous single thread channel to a low sinuosity braided channel is considered to be a major channel change. The Scottish examples however appear to be less sensitive to climatic change (Werritty and Leys, 2001). This may be because they are adjusted to episodes of very high discharges and sediment loads typical of mountainous catchments (Werritty, 1997b). Whereas changes in flood frequency in the Tyne and Severn catchments initiate channel metamorphosis producing a new planform configuration. However metal mining has also influenced river activity in the Welsh upland and Pennines. With the exception of the upper Clyde catchment (Rowan et al., 1995) the impact of metal mining is not well documented in Scotland. None of the rivers considered by Werritty and Leys (2001) were affected by metal mining. Werritty and Leys (2001) cite the presence or absence of historic metal mining as the cause of the differing sensitivity between their Scottish rivers and those of the Welsh and Pennine uplands. There remain complications however, as not all examples of planform change in the

Pennines occurred in mined catchments such as Thinhope (Macklin et al., 1994). The impact of metal mining is discussed in section 2.3.2.1.

2.3.1.2 Convective storm events

Intense rainfall events associated with thermally convective thunderstorms have been documented throughout the British uplands (Carling, 1986a; Harvey, 1986; McEwen and Werritty, 1988). These storm events are not necessarily associated with a particular climate circulation pattern, although meridional circulation patterns may encourage these, due to stationary blocking conditions which arise from high amplitude wave development within the circumpolar air streams (Rumsby and Macklin, 1994). The intensity of rainfall during a convective storm has resulted in the term cloudburst being used to describe such events (Huddleston, 1930). Rainfall patterns are spatially discontinuous, with intense rainfall centres over relatively small areas and relatively light rainfall in surrounding areas (Carling, 1986a; Harvey, 1986). Within these storms, rainfall totals of >50 mm in an hour (return period over 100 years) (Harvey, 1986), 80 mm over 2 hours (return period ~1400 years) and 87 mm in 3 hours (return period 400 years) (Carling, 1986a; b) have been recorded.

Dramatic channel planform changes occur rapidly during the resulting floods, rather than gradually in response to decadal climatic changes. For example, rapid change such as channel avulsion along the Allt Dubhaig in the Scottish Highlands and floodplain reworking with meander removal along the Cleekhin Burn in the Scottish Borders have been linked to the passage of anomalously large flood events (Werritty and Leys, 2001). The geomorphological impacts of these storm events on river channels are dependent on the location of the storm within the catchment. In high relief areas with pronounced lateral confinement, such as headwater streams (Carling, 1987) and mountain torrents (McEwen and Werritty, 1988) lateral channel shift may be inhibited. However, pronounced vertical incision (Carling, 1986a) can lead to high sediment entrainment incorporating large boulders (Johnson and Warburton, 2002) and, where sediment supply is sufficient, debris flows (Carling, 1987). Such high sediment loads are promoted by hillslope erosion including slides and gully erosion (Harvey, 1986). Where lateral confinement diminishes, high discharge and sediment loads can lead to significant planform change (Werritty, 1997a). Where the valley flood width alternates between narrow and wide sections, a corresponding pattern of alternating erosion and deposition can occur (Macklin, 1997d).

Carling (1986a) described channel changes along Langdon Beck, a sinuous single thread stream in the North Pennines, following a convective storm event in 1983. Here, chutes were excavated across channel bends, often encouraged by deposition within the bends. At their confluence with the main channel, tributary streams deposited gravel often filling the trunk channel. Boulder jams also occurred; these constrictions lead to downstream scour associated with increased turbulence and loss of sediment to storage above the jam (Carling, 1986a). Similar, but more widespread styles of planform change were described following a flood of similar magnitude on Exmoor in 1952 (Anderson and Calver, 1977). Valley floor width and sediment availability strongly influenced planform changes (Anderson and Calver, 1980). This is particularly significant in single thread channels where active sediment sources are limited. Subsequent to the flood channels can adjust back to a planform similar to that before the flood (Carling, 1986a), however planform adjustments since the Exmoor flood have been relatively minor and the channel retains the post-flood planform (Anderson and Calver, 1980).

A major storm in the Howgill Fells during 1982 (Harvey, 1986) resulted in slope failures, reactivation of gully systems and alluvial fan sedimentation. Despite some loss of sediment to storage in alluvial fans, sufficient quantities of sediment were delivered to the channel network to induce channel metamorphosis (Harvey, 1991), and previously single thread channels developed braided planforms. In the years following the flood the river channels in the Howgill Fells incised through the flood deposits and re-established a planform and bed structure similar to that prior to the flood. Storm events may therefore initiate coupling within the fluvial system, however this is only a temporary response to the event, with subsequent catchment recovery effectively de-coupling the system.

Typically the spatial extent of convective storm impacts are limited. For example, impacts associated with the 1983 storm event in the North Pennines (Carling, 1986a; Carling, 1986b) were confined to tributary streams rather than the main trunk channel of the wider catchment, where limited impacts were experienced (Archer, 1992). Flood discharge at the catchment mouth of Langdon Beck catchment for example, had an 8-20 year return period as opposed to the storm event in the catchment head that had a return period of 400 years (Carling, 1986a).

2.3.2 Catchment land use

2.3.2.1 Metal mining

The impact of metal mining on fluvial systems has attracted considerable attention, due both to concerns about the environmental impacts of pollution released and the impact of increased sediment release on channel planform. Significant impacts have been reported from the uplands of mid Wales (Lewin et al., 1983; Taylor and Lewin, 1996), the Yorkshire Dales (Dennis et al., 2003), the North Pennines (Aspinall et al., 1986; Aspinall and Macklin, 1985; Macklin, 1986a; Macklin and Lewin, 1989; Warburton et al., 2002) and the Lowther Hills in the Scottish Borders (Rowan et al., 1995). Similar impacts have also been reported downstream of metal mines in Poland (Macklin and Klimek, 1992), Tasmania (Knighton, 1987, 1989, 1991), Bolivia (Miller et al., 2002) and Southwest Spain (Hudson-Edwards et al., 1999b).

Metal mining in the British uplands has been carried out since Roman times (White, 1988). Roman mining is likely to have been piecemeal in nature and confined to working exposed veins (White, 1998) which resulted in negligible geomorphological impacts. With the expansion of mining during medieval times from the fifteenth century onwards (Lewin and Macklin, 1987), mining began to influence catchment geomorphology (Higgitt et al., 2001). Aided by technological developments such as water wheels and water pressure engines (White, 1998), metal mining in the British upland expanded considerably during the 18th and 19th centuries (Raistrick and Jennings, 1965). Figure 2.5 shows the distribution of metal ore fields in Britain. Reported geomorphological impacts have primarily been associated with lead and zinc extraction during the 18th and 19th centuries. Table 2.2 shows lead and zinc output for the major British ore fields.

Metal mining can have a range of influences on the fluvial system in upland catchments. Of particular significance is the impact of mining on sediment supply to the river channel network. Estimates based on rock removal in the North Pennines during the late 19th century suggest sediment yields of $200 \text{ t km}^{-2} \text{ yr}^{-1}$; approximately ten times current stream loads (Higgitt et al., 2001). Sediment delivery to river channels took the form of both coarse (bedload calibre) sediments and fine suspended loads (Lewin and Macklin, 1987).

Figure 2.5 The distribution of Ore Fields in the Britain (excluding Ireland)
Modified from Lewin and Macklin, 1987).

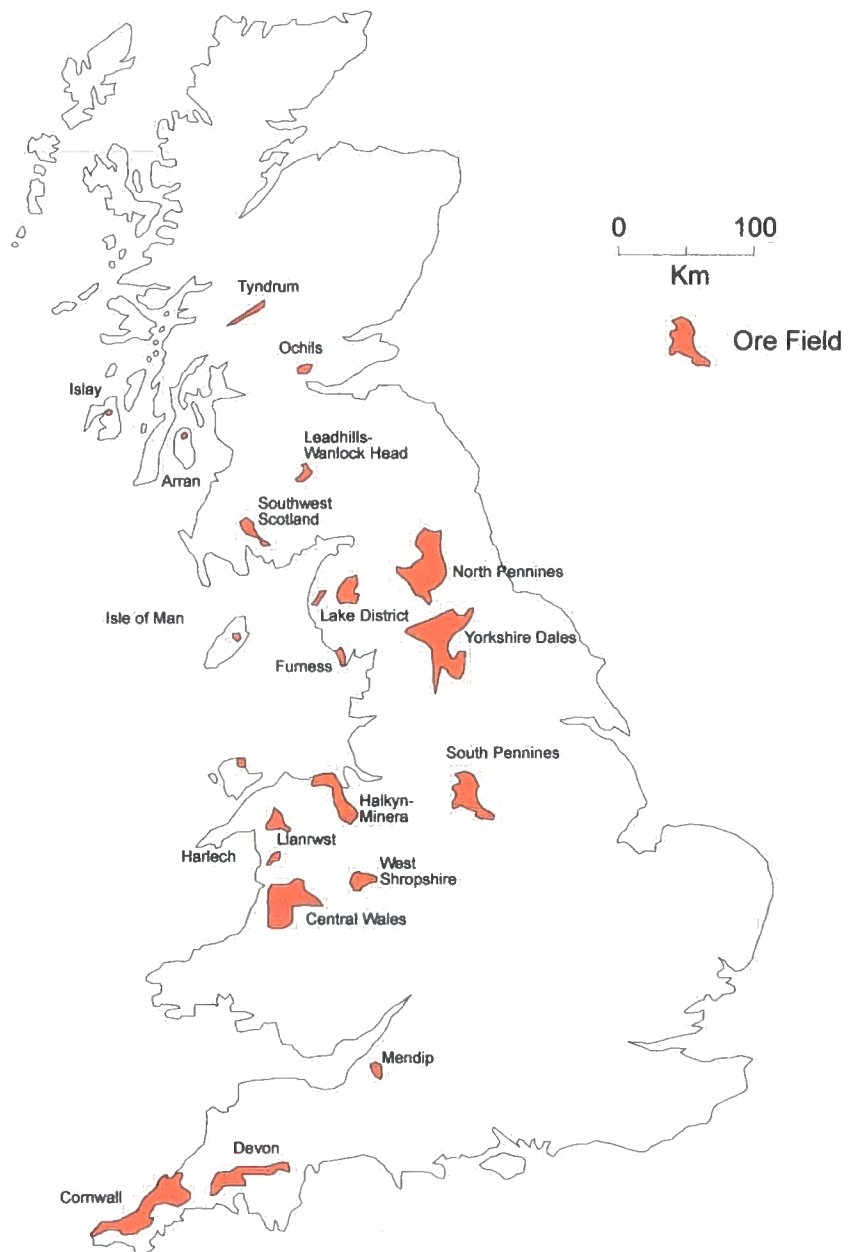


Table 2.2 Lead and Zinc concentrate output ('000 tonnes) for the major British Ore fields (modified from Lewin and Macklin, 1987, p1010)

Ore field	Lead	Zinc
North Pennines	4000	267
Lake District	226*	34
Derbyshire	678 [#]	91 [#]
West Shropshire	237	21
Central Wales	479	151
Llanrwst-Harlech (N.W. Wales)	47	33
Halkyn-Minera (N.E. Wales)	1870	290
Mendip	200	?
Devon-Cornwall	322	89
South West Scotland	317	14
Isle of Man	268	256

*90% from Greenside Mine

[#] 70% Lead and nearly 100% zinc from Mill Close Mine

The volume of coarse sediment delivery is influenced by the proximity of the mine to the river channel, the duration and intensity of extraction and perhaps most significantly the mining technique employed. Mining techniques ranged from open cast workings, the excavation of shafts and adits to hushing. Coarse sediment may be introduced to the channel where mining operations were carried out in close proximity to the river channel, for example where river channels undermine spoil heap material (Kondolf et al., 2002). Of the range of mining practices, hushing has left the most dramatic impact on the landscape (White, 1998).

Hushing is a hydraulic mining technique that involved constructing a reservoir above a mineral vein. Subsequently controlled releases of water were then used to expose the vein and remove rock overburden (White, 1998). This produced a deep linear gully across the hillside. Hushing was most frequently used in the North Pennines and Yorkshire Dales with some examples in mid and south Wales (Cranstone, 1992). Hushing was practiced primarily during the 17th and 18th century and declined after the early 19th century (Cranstone, 1992). The differing sizes and locations of hushes suggest that hushing was used for a range of different purposes. Prospecting for new veins and exposing known veins resulted in relatively small hushes as compared to deeply excavated exploitation hushes from which ore was extracted. Hushes are also thought to have formed by the practice of using natural streams to wash tailings and spoil, these are termed washing hushes (Cranstone, 1992). The quantity of sediment transferred from hushes to the river channel is reliant on the degree to which the

hush and channel are coupled. Examples of debris fans at the base of hushes suggest that some sediment was stored at the base in these fans (Holliday, 2003). The quantity of sediment which moved directly into the river channel is difficult to quantify, but may have been substantial as examples of channel transformation have been recorded downstream of hushes (Macklin, 1997a).

Subsequent to extraction, on-site processing was undertaken. This involved crushing, dressing and milling, followed by the separation of ore by gravity in running water (Bowes and Proud, 1984). This waste then passed directly into river channels (Lewin and Macklin, 1987). Metals entered the channel either as fine sediment or as simple ions. However particulate dispersal dominated, as ions react with and are complexed by organic material and fine-grained sediments (Macklin, 1992). The dispersal of fine-grained sediment within the fluvial system was not confined to high flows although flood stage transport and over bank deposition was also important (Lewin and Macklin, 1987). Contaminant dispersal was influenced by hydraulic sorting due to differential particle density and size (Aspinall and Macklin, 1985; Lewin and Macklin, 1987). For example, cadmium, silver and zinc dispersal was more extensive than copper or lead in the Alston Moor and Allendale mining areas of the North Pennines (Macklin and Smith, 1990). Mixing with uncontaminated sediment reduces the concentration of mining waste with distance downstream from the mine (Macklin, 1992).

Deposition of heavy metal contaminated fine sediment has been widely reported in mined catchments (Dennis et al., 2003; Hudson-Edwards et al., 1997; Passmore et al., 1992). The distribution of heavy metals across floodplain and terrace surfaces is complex. The styles, rates and distribution of contaminated sediment vary in relation to the timing and duration of mining inputs (Hudson-Edwards et al., 1999a). Floodplain topography, influencing frequency of inundation, and degree of lateral re-working strongly control the distribution of contaminants (Brewer and Taylor, 1997). The vertical distribution of heavy metal contamination is also highly variable, reflecting not only changes in mining output but also post-depositional leaching, translocation and migration of metal enriched ground water (Taylor, 1996).

Mining waste input can have a variety of impacts on the fluvial system. Contaminated sediments may be transferred through the fluvial system with little impact on channel stability; this has been termed passive dispersal (Lewin and Macklin, 1987). Metal contaminated sediment is deposited either within the channel or on the surrounding

floodplain with no impact on channel change (Taylor and Macklin, 1998). Under such conditions metal concentrations in floodplain sediments are related to the frequency of inundation by flood events. Spatial concentrations of heavy metals decrease with distance from the channel. Sub-surface sediment sequences show increasing metal content near the surface associated with nineteenth century mining activities (Taylor and Macklin, 1997). Where the deposition of contaminated sediment is coincident with channel migration (the age of alluvium increases with distance from the channel) changes in heavy metal contamination across the floodplain reflect the changing quantities of metal pollution released overtime (Wolfenden and Lewin, 1977). At the catchment-scale the timing of metal contaminated sediment deposition occurs progressively later downstream reflecting sediment transfer rates (Lewin and Macklin, 1987).

Fine sediment dispersal can lead to channel destabilisation. Heavy metal concentrations recorded in mining age sediments are often an order of magnitude higher than in uncontaminated soils (Macklin and Smith, 1990). Contaminated sediment retards riparian vegetation cover, which increases the removal of cohesive fine sediment from the floodplain and ultimately causes riverbank destabilisation (Lewin et al., 1983). Bank destabilisation promotes channel instability both through bank retreat and by introducing additional coarse sediment into the channel.

Locally inputs of coarse sediment during mining operations can have a more significant impact on channel morphology than the introduction of fine sediment. Direct inputs of coarse sediments to river channels have been linked to reach-scale channel metamorphosis from a single thread to braided planform (Lewin et al., 1983; Macklin, 1986a). Recent evidence has suggested that relatively small volumes of coarse sediment delivery may be sufficient to cause channel changes in headwater streams, through channel avulsion (Warburton et al., 2002). Many recorded examples of planform transformations, in particular the onset of channel braiding, occurred during the mid-nineteenth century (Lewin et al., 1983; Macklin, 1986a; Macklin and Lewin, 1989; Passmore et al., 1993). This may be linked to the intensification of mining during the late 18th and early 19th century. Prior to this increased sediment input, sediment released by mining does not appear to have influenced channel planform (Macklin, 1986b).

2.3.2.2 Deforestation and Afforestation

Deforestation in the British uplands was spatially and temporally variable. Forest clearance in the North Pennines, indicated by pollen sequences, is considered to have occurred during the late Iron Age / Early Roman period (2,200 BP) (Roberts et al., 1972; Turner, 1979). Episodes of woodland clearance and cultivation at Callaly Moor in Northumberland have been dated to the mid-Bronze age (~3,000 BP) (Macklin et al., 1991). Near total woodland clearance in the Bowmont Valley during the late Iron Age (2,200 BP) (Tipping, 1994) is thought to have been associated with deforestation throughout the Cheviot Hills, Northumberland (Harrison and Tipping, 1994). Significant forest clearance in Upper Annandale, Southern Scotland is believed to have occurred during the Romano-British Period (1,300 BP) to make way for arable and pastoral agriculture (Tipping et al., 1999). However earlier clearance in the upland areas of the catchment is indicated by grazing indicator taxa, this dates to 2,700 BP (Tipping et al., 1999).

Dated alluvial deposits indicate deforestation was coincident with phases of river channel alluviation during the Holocene (Macklin et al., 1991). Vegetation destruction lowers the threshold for erosion and may have triggered gullyng on slopes (Macklin et al., 1994). Reduced interception and evaporation rates result in increased runoff, particularly flood magnitudes (Knox, 1977) in tributary catchments. This would have promoted sediment removal (Knox, 1987, Macklin et al., 1992a). Sediment liberation in headwater streams appears to have resulted in extensive trunk channel aggradation (Macklin et al., 1991). Although widespread deforestation was essentially complete by historic times (last 150 years), it remains significant in upland catchments as low interception and evaporation rates make these catchments sensitive to climatic events (Macklin, 1999).

Recent afforestation in the British uplands has predominantly taken the form of conifer plantations. At its peak during the early 1970s 40,000 ha yr⁻¹ were being planted (Robinson and Blyth, 1982). These plantations account for more than one half of the woodland area of Britain, which in itself constitutes 10% of the total land area (Archer and Newson, 2002). Afforestation in the uplands has typically been carried out on poorly drained soils including peat. This has required ground preparations involving cultivation and open ditch drainage (Archer and Newson, 2002). These preparations involve ploughing furrows up and down slopes to drain the soil creating turfs into which trees can be planted. The down slope ends of furrows

are connected by shallow sloping cross furrow drains leading to water courses (Stott, 1997b). Ground preparations result in increased runoff with flashy flood peaks (Stott, 1989), which persists until canopy closure (Robinson, 1998).

Ground preparation techniques have also been associated with increased sediment yield, both as suspended sediment (Stott, 1989) and bedload (Newson, 1980; Stott, 1997b). Stott (1997) reported bedload yields 3-7 times higher than neighbouring catchments with rough pasture or moorland. Increases in sediment load are also associated with timber harvesting operations (Stott, 1989). Newson (1981) recorded bed load yields over 17 times greater than that of adjacent grassland following forest clearance in mid-Wales. Following canopy closure increased evaporation on rough conifer canopies leads to water losses higher than those from moorland vegetation (Calder, 1990). Research at Balquhiddy, for example, has revealed that peak discharges from mature forested catchments are lower than adjacent moorland catchments (Stott, 1997a). Transpiration by mature trees is likely to lower the water table to a level lower than the ploughed depth (Lane et al., 2002). Afforestation does not appear to increase flood magnitude or decrease the duration of floods (Archer and Newson, 2002).

Research into bank erosion rates between forested and non-forested catchments at Balquhiddy in Scotland indicates bank erosion rates can be lower in forested catchments than in surrounding moorland areas (Stott, 1997a). This difference in bank erosion rates has been attributed to a higher incidence of frost processes on riverbanks in exposed moorland. Significantly however, research on the margin of Dartmoor, South West England, revealed high bank erosion rates along channels in forested areas (Murgatroyd and Ternan, 1983). The resulting increase in bank full width induced bed aggradation, leading to wide shallow channels (Murgatroyd and Ternan, 1983). These contrasts in bank erosion response to forestry may relate to local effects such as bank composition. While a relationship between bank erosion and frost action was found in moorland areas at Balquhiddy, this effect may be reduced in Dartmoor due to both its southerly location and lower elevation. Local effects may therefore influence the impact of mature forest on river channel geomorphology. In general, despite decreases in runoff, sediment yields from mature forest can remain high (Stott, 1989).

2.3.2.3 Intensification of agricultural activity

Increases in erosion caused by grazing animals have been documented from around the world (Evans, 1998). In the British uplands livestock grazing has had long history, for example in the North Pennines a phase of woodland clearance for pasture occurred during the twelfth century (Roberts et al, 1972). Grazing was a particularly important land use during the last 200 years (Holliday, 2003). In the British uplands grazing pressures have increased since the 1940s (Evans, 1997). Grazing can have direct impacts on river channels as trampling can lead to increases in bank erosion (Trimble and Mendel, 1995). Of particular concern in the uplands is the impact of grazing in blanket mire areas; increasing grazing pressures during the mid-nineteenth century have been cited as a possible cause of blanket mire erosion (Evans, 1997). Gully erosion in peat catchments reduces the capacity of blanket peat to store rainwater leading to an increase in flood peaks, but can also increase the supply of coarse sediment to the channel network where gullies erode into the substrate (Wishart and Warburton, 2001).

Agricultural land drainage can also influence river channel processes through increased flood frequency and magnitude (Rumsby and Macklin, 1994), and increased sediment delivery to river channels (Newson, 1980b). Government grants were available in the UK for land drainage from the 1940s until 1985 (Archer and Newson, 2002). Drainage was designed to lower the water table to improve grass and heather growth for sheep and grouse. In lowland areas land drainage utilises a network of subsurface pipes, in the uplands however drainage typically consists of open ditches (Longfield and Macklin, 1999).

Moorland drainage (gripping) has attracted attention because it is a significant cause of increased flooding (Caufield, 1982). Limited peatland drainage was instigated in some upland areas prior to 1628 associated with peat cutting (Ardron et al., 1997). Gripping in the Pennine uplands began during the 1940s in response to grant-aid during the Second World War to expand livestock numbers; these grants remained in place until the 1960s (Longfield and Macklin, 1999). Moorland gripping is also used as a preparation technique prior to afforestation; examples include Upper Wharfedale (Lane et al., 2002) and the Cheviot Hills (Wishart and Warburton, 2001). Gripping can increase flooding via two mechanisms. Firstly, limited water table lowering encourages water to flow through the upper layers of the peat, which is then intercepted by the grip network and diverted to stream channels. Excessive water

table lowering can, however, reduce flood peaks due to increased storage capacity of the peat (Lane et al., 2002). Secondly, grips reduce the distances that water needs to travel to reach the stream network, which decreases the time to flood peak in the channels downstream (Lane et al., 2002).

In addition to impacts on flooding, drainage ditches may also increase the delivery of bed-load calibre sediment to river channels (Newson, 1980b). This increase in sediment yield results from erosion of both the bed and banks of the ditches. Newson (1980b) found erosion of ditches lead to significant sedimentation problems including the deposition of fans of gravel below eroding ditches and reservoir sedimentation. Ditch design exerts a significant control on the ditch erosion problems, those excavated into cohesive peat substrate were found to be stable on slopes of up to 15°, however ditches dug into uncohesive colluvium became unstable on slopes greater than 2° initiating scour and drain enlargement (Newson, 1980b).

2.3.3 Direct anthropogenic channel modification

Anthropogenic modifications to river channels take a range of different forms. The most widely reported examples are channelization, reservoir impoundment, gravel extraction and flood embankment construction. Interferences such as these can have both local impacts at the point of interference and indirect impacts both upstream and downstream (Kondolf, 1997). The occurrence of the influences in British upland catchments has been reported, however the precise importance of these impacts is yet to be fully evaluated (Newson, 2003). This section considers each of the main forms of interference in turn and considers both proximal and distal impacts and examines the timescales at which these operate.

2.3.3.1 Channelization

Channelization is a general term encompassing various forms of channel engineering to facilitate flood control, drainage improvement, navigation, and erosion prevention (Knighton, 1998). Channelization of rivers in England and Wales has a long history but increased dramatically between 1930 and 1980 when 8500 km of river channelization was implemented (Brookes et al., 1983). The range of different channelization techniques is summarised in Table 2.3. Of these, channel straightening leads to the most profound downstream impacts (Brookes, 1985). Removing bends decreases the path of the channel therefore increasing the slope,

which increases flow velocity and transport capacity, which then erodes the riverbed creating a knickpoint that migrates upstream (Knighton, 1998). Upon leaving the channelized reach this sediment charged flow loses power due to the decrease in gradient. This reduces the transporting capacity of the flow resulting in deposition, which leads to channel instability (Knighton, 1998). Downstream, effects below resectioning works produce an erosional response, which can increase channel size by as much as 153% (Brookes, 1987). Typically this involves an increase of width rather than depth as channel bed armour restricts down cutting. However, channel response to resectioning work is dependent upon flow power and only appears to be significant in channels with high stream power (Brookes, 1987). Where sediment supply is sufficient localised deposition within the channelized reach can lead to channel destabilisation, particularly bank erosion (Leeks et al., 1988). Over longer periods bar deposition and associated bank erosion can lead to the re-establishment of a meander channel planform (Lewin, 1976).

Table 2.3 River channelisation techniques (modified from Knighton, 1998, p 312).

Technique	Description
Straightening	River shortened by artificial cutoffs, steepening the gradient and increasing flow velocity
Resectioning	Widening and/or deepening the channel to increase its conveyance capacity to reduce the incidence of overbank flooding
Flood embankment construction	Channel banks raised or embankments constructed along the river banks to confine flood waters
Bank protection	Use of structures such as gabions and steel piles to control bank erosion
Clearing and snagging	Removal of obstructions from the water course to decrease resistance and increase flow velocity

Flood embankment construction has been carried out in the British uplands since the nineteenth century (Winterbottom, 2000). Embankment construction has predominantly been carried out in a piecemeal fashion. For example the upper reaches of the River Tyne in the North Pennines were embanked locally throughout the nineteenth century (Passmore et al., 1993; Rumsby and Macklin, 1994). Flood embankment construction prevents floodplain inundation during flood events, which increases channel discharge and encourages erosion. Channel incision in the Tyne basin appears to have been encouraged by flood embankment construction (Rumsby and Macklin, 1994). In sedimentation zones characterised by historic channel division

in the Upper South Tyne Valley, stone embankments were constructed to close off dead channels during the early twentieth century (Passmore et al., 1993). This also prevented the dissipation of flow during flood events and encouraged channel incision. The decline in examples of braided rivers in Scotland since the nineteenth century has also been attributed to embankment construction (Gilvear, 1993). Channel confinement by flood embankments has reduced channel braiding on the Rivers Tummel and Tay (Winterbottom, 2000) and also the River Dee (McEwen, 1989).

Bank protection works such as gabions tend to be used in specific locations to prevent bank erosion. Bank protection works inhibit channel mobility during floods and contributed to the decline in channel braiding on the lower Spey in Scotland (Lewin and Weir, 1977). More extensive bank reinforcement works have been undertaken where river channel courses have been artificially altered. For example gabions were installed along a straightened section of the Afon Trannon in mid-Wales in an attempt to reduce the impact of channel readjustment following earlier channelization (Leeks et al., 1988).

2.3.3.2 Reservoir impoundment (flow regulation)

Discharge regulation by reservoir construction began in 1891 with the completion of the Vyrnwy Reservoir in northern Wales (Higgs and Petts, 1988) although some small-scale reservoir schemes predated this. Since the 1950s the number of reservoirs has doubled globally (Beaumont, 1978). The impacts of reservoir construction have been reviewed in a number of papers such as Petts (1979) and Carling (1988). Reservoirs alter river channel planform downstream through modifications to flood frequency and magnitude and alterations to river sediment loads (Petts, 1979). Due to reduced sediment loads bed erosion occurs immediately downstream of dams and proceeds until channel slope declines and bed roughness increases, reducing the flow velocity to below the threshold for sediment transport (Petts, 1979). Bed armouring due to winnowing of fine sediment may also inhibit this incision. Incision is often only the first phase of channel adjustment, which ultimately affects the river system for some distance (Petts, 1979). Aggradation occurs due to reduced peak discharges and therefore reduced bedload transport rates. This is particularly significant at tributary junctions where the bed load from tributaries is deposited (Petts and Thoms, 1987). Alluvial channels subject to competent

discharges adjust by redistributing floodplain sediments via erosion and deposition to reduce channel width. Such changes will occur gradually, due to the reduced frequency of competent discharges. Flow regulation of Welsh rivers appears to have reduced competent discharges significantly, causing a reduction in active gravel bar extents via reductions in sediment supply rates and decreased frequencies of bar inundation (Brewer et al., 2000). As the significance of areas of non-regulated catchment increases downstream, the impact of regulation on channel capacity will decrease, to a point where no channel changes are induced by impoundment.

2.3.3.3 Gravel extraction

Gravel extraction from British rivers was widespread between the mid 1940s and the early 1970s (Newton, 1971). Relatively few accounts of the impact on gravel extraction on British Rivers have been published (McEwen and Gardiner, 2000; Newson and Leeks, 1986; Sear and Archer, 1998). Gravel extraction from river channels can have a number of impacts. Excavations within the river lower the bed level, leading to a localised gradient increase, which increases flow power and promotes bed erosion. This erosion is further promoted by the disruption to bed armour caused by excavations (Mossa and McLean, 1997). Localised bed erosion produces a knick-point that migrates up stream as erosion progresses (Kondolf, 1994). Upstream knick-point progression can undermine structures within the channel upstream, such as bridge piers (Kondolf and Swanson, 1993). It has also been suggested that sediment load diminution due to deposition in the lowered section can promote downstream incision (Kondolf, 1994). Water leaving the extraction site has an excess of energy that then erodes the bed and banks (Kondolf, 1997). Finally channel incision leads to a lowering of the water table of the surrounding floodplain, which can affect riparian vegetation and agriculture (Kondolf, 1994).

Channel incision increases bank heights, and triggers bank erosion, which can promote channel instability through channel widening (Sear and Archer, 1998). The nature of channel instability induced by gravel extraction is dependant upon bank stability and sediment supply to the reach, which will increase as incision progresses upstream. Assuming an initially single thread planform, gravel extraction operations promote the development of a braided planform. This is due to increased sediment supply from knick-point migration, and additions from increasing bank erosion. Over

widening of the reach during extraction operation dissipates flow power, encouraging bar deposition. Despite initial planform stability downstream caused by incision, in the long-term aggradation may begin to dominate as increasing planform instability in the extracted reach increases sediment delivery downstream (Sear and Archer, 1998). The magnitude and direction of planform response is however controlled by factors such as bank erodibility variations, sediment availability and flood frequency and magnitude.

In many British catchments channel gravel extraction is seldom considered to be a primary control on channel planform. Despite recognising that extraction has taken place from a river many studies do not offer a detailed consideration of the potential impacts on the river channel. For example, gravel extraction from the South Tyne during the twentieth century is considered a potential cause of channel incision (Passmore et al., 1993) yet this has not received the same attention as flood frequency or metal mining impacts. Localised extraction impacts have been reported, such as 2.5 m of incision of the River South Tyne at Beltingham/Bardon Mill since the 1960s, yet these are not discussed in a wider context (Macklin and Smith, 1990). Recent work in the Tyne catchment has revealed that gravel extraction was carried out extensively along the lower Tyne and South Tyne as far upstream as Haltwhistle, resulting in pronounced bed incision throughout (Archer, 2000; 2003).

2.3.4 Geomorphological setting

2.3.4.1 Catchment structure

As described above, changes in sediment supply and discharge regime due to climatic and anthropogenic influences have been identified as a significant cause of planform change in upland catchments. However sediment supply is also related to the geomorphology of the catchment. The number and location of sediment sources is related to the geomorphological structure of the catchment. Sediment sources include local slope-channel contacts and sites of bank erosion. The significance of slope-channel linkages depends upon the extent to which the channels and slopes are coupled. Intervening floodplains effectively decouple channels from slopes and only infrequent contacts with sediment sources occur as river channels migrate across the floodplain. Newson (1981) describes a characteristic of montane channels to be the lack of a floodplain, however there is considerable variation in the British

uplands. Of particular significance in the British uplands is the legacy of Quaternary glaciation (Newson, 1981). Accumulations of Quaternary sediments are significant throughout the British uplands. These may take the form of cross-valley moraines (Howard et al., 1998), large solifluction sheets (Harrison, 1993), or Late Glacial outwash deposits preserved as river terraces (Macklin et al., 1992a). These unconsolidated sediments frequently confine river channels in the British uplands and can be locally significant sediment sources (Passmore and Macklin, 2000).

Alternating patterns of laterally stable transportation reaches and laterally unstable deposition reaches (sedimentation zones) are characteristic of wandering gravel bed-rivers (Church, 1983). Such patterns of transport and deposition have been identified in the British uplands (Macklin and Lewin, 1989). However rather than simply reflecting the passage of pulses of sediment, their distribution and character are controlled in part by the topography of the valley (Richards, 2002). In the British uplands Quaternary sediments and bedrock exposures confine channel pattern to a single thread planform and prevent within-channel sedimentation. Where confinement diminishes, channel sedimentation can occur.

The susceptibility of riverbanks to erosion controls planform on two levels: first high bank erodibility increases sediment delivery to the river channel and second, erosive banks encourage planform migration. Fluvial processes in upland catchments are dominated by bed-load sediment regimes with reworking of coarse sediment (Newson, 1981). Riverbanks are typically composed of uncohesive sediments capped by a relatively thin layer of finer sediment. Subaerial processes are a significant contributor to bank erosion rates as these prepare riverbanks for fluvial erosion (Couper and Maddock, 2001). Such processes are particularly significant in upland catchments due to the increased incidence of frost action and pre-wetting processes enhanced by high precipitation (Lawler et al., 1999). However bank erosion rates are also dependent on stream power. Conceptual modelling of bank erosion rates throughout a catchment predicts that bank erosion rates will peak in the middle reaches of the catchment where high stream power increases sediment entrainment (Lawler, 1992). This analysis is supported by evidence from the Swale-Ouse catchment, where highest bank erosion rates were recorded in the piedmont zone (Lawler et al., 1999). This confirms Newson's (1981) assertion of the significance of piedmont reaches and also explains the large numbers of recorded instances of planform change in piedmont settings (Brewer and Lewin, 1998; Hooke,

1995; Macklin and Lewin, 1989; Passmore and Macklin, 2000; Sear and Archer, 1998).

The gradient of the valley floor along which a channel flows is a key control on channel planform. This is perhaps best illustrated by the Allt Dubhaig in the central Scottish Highlands, which has a markedly concave long profile giving a significant decline in channel gradient over a distance of 3 km. The channel planform of the stream changes progressively downstream in response to the reduction in gradient (Ferguson and Ashworth, 1991). In the upper steepest reaches the channel is mildly braided with coarse bed material. As the gradient declines downstream the channel adopts a predominantly meandering planform with point bar chutes. Further downstream where the gradient is lowest, point bar chutes are not present. Increased bend stability occurs with decreasing gradient lower in the valley. The decline in channel gradient also results in a reduction in the grain size of the bed sediments of the channel. These changes in channel planform and sediment size reflect the decline in flow power (shear stress) as gradient declines (Ferguson and Ashworth, 1991).

2.3.4.2 Feedback mechanisms

Feedback mechanisms operating within the fluvial system can control the nature and timing of planform change over a wide spatial scale. Pulses of sediment delivery from tributaries can be related to intrinsic feedback mechanisms (Schumm, 1993). Tributary rejuvenation (via base level change) initiates incision that propagates up the tributary; this increases sediment supply to the main channel which causes channel aggradation. Progressive aggradation increases the slope of the trunk channel. This ultimately increases flow power and favours a switch to incision, which can then rejuvenate the tributaries repeating the cycle (Schumm, 1993). A similar feedback relationship was observed by Harvey (1991) in the Howgill Fells. Multiple sediment production events each year in tributary gullies build debris cones at the base of the gully, which lowers the gully gradient. When cones are removed by periodic flooding every 2-5 years this initiates gully incision. If cones were not removed the gullies would stabilise and vegetate (Harvey, 1991).

The scale at which feedback mechanisms operate in the fluvial system is highly variable. At the scale of an individual bar, sedimentation within the channel can lead to increased bank erosion due to flow diversion against banks and decreased channel capacity. Significantly, channel widening due to high bank erosion rates

encourages bar development through flow dissipation and increased sediment delivery. Neck cut-off in meandering reaches following progressive bend erosion increases the channel gradient and leads to widening of the channel in the years following cut-off, which encourages sedimentation (Hooke, 1995). Deposition within the channel increases bed-roughness, which compensates for increased gradient. The effects of neck cut-off can be transmitted both upstream and downstream, however this is dependent on bank erodibility (Hooke, 1995).

The development of valley constrictions can act in a similar manner to base level rise. For example the Allt Lorgaidh, a tributary of the River Feshie in the Scottish Highlands, deposited an alluvial fan which constricted the valley of the Feshie. This induced channel aggradation promoting channel braiding (Richards, 2002). Eventually progressive valley floor aggradation will create a gradient across the toe of the fan which initiates scour at the base of the fan. Removing this base level increase leads to incision up the main valley promoting terrace development (Richards, 2002).

2.3.5 Sediment transfer in upland catchments

The factors discussed above influence channel planform through their impact on the balance between discharge and sediment supply. The distribution of consequent changes to river channel planform throughout a catchment is determined by the quantity and rate of sediment transfer through the catchment. The sediment transfer rates are crucial as this determines the timing of changes to the balance between discharge and sediment downstream. The volume and rate of sediment moved downstream determines the nature of channel planform changes which occur. Land use changes can lead to pulses of sediment delivery to the channel network, this material then migrates downstream as a wave (Hoey, 1992), transforming the channel planform from single thread to braided (Nicholas et al., 1995).

Sediment transfer within the fluvial system is inherently episodic (Schumm, 1977). This is because sediment transport is a power function of discharge; high flows carry proportionately higher sediment load than moderate flows (Kondolf, 1994), although the development of an armoured layer can restrict the supply of sediment (Knighton, 1998). As a result, transport rate tends to be higher on the recession limb of a flood hydrograph as the armoured layer restricts transport until this is broken (Kondolf,

1994). The intermittent nature of both anthropogenic activities and the occurrences of discharges competent to move bedload make the generation of sediment slugs likely in upland catchments (Lewin and Macklin, 1987). It is now recognised that a significant proportion of sediment transfer occurs in sediment slugs (Nicholas et al., 1995). Bed load slugs can be generated either through intrinsic change in sediment generation (endogenous waves) such as channel avulsion (Wathen and Hoey, 1998) or external changes (exogenous waves) in the rate of sediment delivery for example due to mining operations (Knighton, 1989). Sediment waves can have a significant impact on channel morphology, and have been implicated in cases of channel planform transformations in upland Britain (Macklin, 1986a).

The coincidence of metal mining activity and a large flood in the catchment of the River Nent in the upper catchment of the South Tyne appears to have generated a slug of coarse sediment (Macklin, 1986a). The downstream migration of this sediment body initiated channel instability and planform metamorphosis. The movement of the sediment slug is indicated by the progressive deactivation of gravel bars in a downstream direction (Macklin, 1986a). Patterns of downstream migration of channel instability (braiding), despite general trends towards channel rationalization, provide further indications of the movement of sediment slugs. Examples of bank and bar activation in the lower South Tyne during the early twentieth century provide an example of this (Passmore et al., 1993). Pulsed delivery of sediment due to deforestation (Roberts and Church, 1986) or climate induced changes in flood frequency and magnitude (Rumsby and Macklin, 1994) also favour the development of sediment slugs. Many other examples of sediment waves have been identified from around the world and have been reviewed by Nicholas et al; (1995).

The magnitude of channel planform change is determined by the size of the sediment slug and as such slugs are classified according to their size (Table 2.4). Megaslugs and superslugs can result in the replacement of natural bed load and result in whole scale re-organisation of valley floor morphology (Knighton, 1989). At smaller scales however the influence of sediment slugs may be modulated by antecedent conditions. Reaches have been identified where no planform change is initiated; these are regarded as transfer reaches (Church and Jones, 1982). These reaches can store sediment which interacts with sediment slugs, exchanging material rather than allowing uninterrupted transfer (Wathen and Hoey, 1998). Alternatively reaches

where planform change occurs are termed sedimentation zones (Church and Jones, 1982).

Table 2.4 Classification of sediment slugs (after Hoey, 1992; Nicholas *et al.*, 1995)

Scale	Wavelength (m)	Controls	Impact on fluvial system
Mesoscale (Mesoslug)	10^1 - 10^2	Fluvial process-form interactions	None or very minor – riffle migration
Macroscale (Macroslug)	10^1 - 10^3	Fluvial process-form interactions	Minor channel change – local bar re-organisation
Megascale (Megslug)	$>10^3$	Local sediment supply and valley floor configuration	Major channel change – bar assemblage re-organisation
Superscale (Superslug)	Basin scale	Basin-scale sediment supply	Major valley floor adjustment – channel avulsion.

The arrival of a sediment slug in a reach is often indicated by aggradation of the riverbed and gravel bar building. In braided rivers this may increase the intensity of braiding (Ashmore, 1991a). In single-thread channels bed load pulses can result in channel division, typical of wandering planforms (Figure 2.1). The response of a reach reflects its sensitivity to the passage of a sediment wave. The sensitivity of the reach may be influenced by intrinsic mechanisms such as bank erodibility, channel gradient and progressive planform evolution that may “prime” a reach leaving it susceptible to perturbations such as flooding (Brewer and Lewin, 1998). Conversely cohesive bank materials or lateral confinement may inhibit lateral migration. The sediment supply history of a reach may exert a significant influence. Progressive patterns of erosion and sedimentation resulting from moderate flood events, for example, can increase the sensitivity of a reach (Fuller *et al.*, 2002). Wathen and Hoey (1998) found that disturbances induced by the movement of a sediment wave can contribute additional sediment to a wave. Such a situation can occur where temporary storage of material exceeds channel capacity, which is termed “over aggradation” (Lane *et al.*, 1996). This is particularly significant where progressive aggradation is occurring in the reach prior to the arrival of a bed load wave. In response to the decrease in capacity the channel erodes, contributing sediment to that sediment wave.

Identifying sediment slugs is highly dependant on the scale of the slug (Table 2.4). The passage of mesoscale slugs that produce very minor changes in channel morphology, such as riffle migration, are only discernable through detailed monitoring

of a riverbed. The small size of these slugs enables their movement to be monitored over a period of years. Larger slugs such as macroscale and megascale slugs are important as these can have significant impacts on channel morphology. Historical analysis of channel planform change can enable the passage of these waves to be discerned, for example through changes in channel planform (Macklin, 1986a). Employing a catchment wide appraisal of channel planform and changes in gravel bar area will therefore allow the movement of these waves to be traced over historic time (150 years). Upland catchments, however, are extremely complex with multiple potential sources of sediment, many of which are capable of generating a sediment slug. The likelihood of disturbances such as metal mining within the catchment, producing clearly discernable sediment slugs, is limited. Pulsed inputs may have been insufficient to generate large slugs discernable from cartographic evidence, and only the merger of small slugs will allow large slugs to form. This is not likely as the variations in the calibre of inputs; timing and travel distances make their coalescence unlikely.

2.3.6 Process interactions

Prevailing climatic regime is the primary driver of planform change in the British uplands over historic timescales through its impact of flood frequency and magnitude (Brewer and Lewin, 1998; Brewer et al., 2000; Harvey, 1991; Macklin et al., 1998; Milne, 1982; Passmore et al., 1993; Rumsby and Macklin, 1994; Rumsby and Macklin, 1996; Werritty and Leys, 2001). However a range of additional processes act to moderate the nature of planform response to climate change. Planform is dependant on the interaction of unique combinations of extrinsic and intrinsic processes. The following discussion explores process interactions in upland catchments with reference to some of the examples outlined in the preceding sections.

Low frequency high magnitude flood events initiated by convective storms can induce rapid and significant channel planform change. However the nature of this impact is controlled by antecedent catchment conditions. In the Howgill Fells the transformation of river channels from single thread to braiding was accomplished due to the input of large quantities of sediment (Harvey, 1991). This sediment originated from numerous dormant valley side gullies, which were reactivated. The origin of these gullies can be traced back to over grazing on these relatively steep slopes

during the Viking Period (Harvey and Renwick, 1987). The intrinsic properties of the catchment such as the close association of river channels and slopes which allowed effective coupling, and the steep gradient of surrounding slopes and gullies make the Howgill Fells sensitive to extrinsic perturbations. In addition to the availability of sediment, valley floor widths were sufficient to allow channel widening and division. These antecedent geomorphological conditions were different to those in the North Pennines which were affected by a similar storm (Carling, 1986a). Here high sediment delivery dominates in laterally confined reaches. Downstream reaches have more extensive floodplains and this inhibited slope-channel coupling so the magnitude of channel response was not as significant. In addition slope failures were dominated by peat slides, which did not liberate large quantities of clastic bed-load sediment (Carling, 1986b).

In catchments where historic metal mining took place, sediment pollution is considered to have had significant impact on channel planform (Lewin et al., 1983; Macklin, 1986a; Macklin and Lewin, 1989). There are few published examples demonstrating channel metamorphosis due to metal mining in the absence of flooding (Lewin et al., 1983). Metal mining appears to increase the sensitivity of river channels to flooding through increased sediment supply, which decreases channel capacity and destabilises riverbanks. Channel destabilisation and the onset of braiding appears to be triggered by flood events, however the magnitude of the channel change is dictated by metal mining (Macklin, 1986a). Similar conditioning by metal mining has been demonstrated elsewhere in the North Pennines in response to relatively low intensity mining (Warburton et al., 2002). Metal mining may have sensitised river channels to such an extent that they moved closer to the threshold for planform metamorphosis, which was then crossed during flood events (Macklin, 1986a).

Passmore et al (1993) noted the persistence of channel braiding in the upper South Tyne catchment during the early twentieth century while channel braiding declined in the lower reaches. This persistence of braiding at a time when flood frequency was declining is likely to be related to a combination of high sediment delivery due to continued metal contamination and greater tributary-channel and slope-channel coupling due to steeper slopes. Despite a decline in the intensity of metal mining during the early twentieth century, continued contamination would have occurred in the upper reaches close to mines due to the reworking of mining spoil (Brewer and Taylor, 1997).

The significance of sediment delivery due to metal mining in conditioning channel response to flooding is supported by the relative lack of significant planform change in Scotland, where mining did not occur (Werritty and Leys, 2001). Despite a similar record of flood frequency and magnitude to the North Pennines and Wales, channel metamorphosis was not recorded except in the case of base level rise. The lack of planform metamorphosis may be partly related to differences in the intrinsic sensitivity of the channel system; mountainous catchments such as those in Scotland contain channels adjusted to high sediment loads. However in the North Pennines the sequence of channel incision recorded in the Thinhope catchment indicates that non-mined tributaries were also sensitive to climate change and contributed large volumes of sediment to trunk channels encouraging channel destabilisation (Macklin et al., 1992b). This sensitivity appears to be related to an earlier phase of deforestation in the catchment (Macklin et al., 1994).

Deforestation causes channel planform change via both aggradation and incision. Initially vegetation removal promotes sediment release leading to aggradation (Macklin et al., 1991). In the British uplands this was reinforced by increased runoff due to climate deterioration (Rumsby and Macklin, 1996). The long-term legacy of woodland clearance, however, is to promote runoff while its impact on sediment production declines in significance, although the resulting channel incision downstream can lead to sediment release. While the majority of woodland clearance in the British uplands took place earlier than the historic period the legacy appears to continue. For example the sequence of terraces in the Thinhope Burn catchment (Macklin et al., 1994) indicate that the catchment remains highly sensitive to climatic variations.

Channel alluviation as a consequence of woodland clearance also appears to be significant elsewhere, for example in Northumberland (Macklin et al., 1991) and the Yorkshire Dales. Catchment sensitivity, similar to that at Thinhope, is evident at Shaw Beck Gill in the Yorkshire Dales (Merrett and Macklin, 1998). Here the catchment also appears to have been sensitised by deforestation, which in this case may not have been complete until the 16th century (Merrett and Macklin, 1998). Significantly however the significance of flood events in Shaw Beck Gill during the late twentieth century may also be related to moorland gripping in the catchment (Merrett and Macklin, 1999).

Anthropogenic modifications to the fluvial system seldom occur in the absence of climate change or geomorphological conditioning. The response of a river channel to anthropogenic modification is influenced by flood frequency and magnitude and sediment supply which are influenced by climate, land use and catchment geomorphology. The coincidence of climatic improvement (decreasing flood frequency and magnitude) flood embankment construction and reservoir construction has been recognised as a cause of planform change, primarily in the form of decreasing channel widths and braiding intensity throughout Europe (Bravard et al., 1997). For example, increasing human intervention since the late 18th Century was related to channel rationalisation in the Danube in Bratislava, Slovakia (Pisut, 2002). Impacts of dams, diversions and bank protection structures constructed in the 1920s to 1950s caused width decrease by 35% and channel change from braided to wandering channel planforms on the Piave River, Italy (Surian, 1999). Elsewhere in Italy up to 50% reduction in channel widths with similar impacts on channel planform have been documented (Surian and Rinaldi, 2003). A combination of climate improvement (at the end of the Little Ice Age) and bank protection structures together with river regulation caused a reduction in channel widths since late 19th Century in Durance River Southern France (Warner, 2000). Where low catchment sediment yields and channelization combine, significant channel incision occurs due to vertical erosion rather than lateral erosion (Wyzga, 2001). In montane and piedmont areas afforestation of floodplains and channelization works caused channel narrowing in southeast France (Liebault and Piegay, 2002). This coincidence of events makes determining the cause of planform change extremely difficult. In Britain however, widespread reservoir construction was typically carried out later than in Europe. Flow regulation associated with dam construction on the River Tummel, Scotland, did not exert an influence until the 1950s, indicating flood embankment construction alone can have a significant impact on channel planform (Winterbottom, 2000).

When assessing the cause of channel planform change it is clearly desirable to consider the full range of processes, both intrinsic and extrinsic. These processes operate at a variety of spatial scales from the regional (climate) to the local (gravel extraction). However the interaction of these processes makes establishing the cause of channel planform change extremely difficult, particularly where differing processes may produce similar channel responses. Individual geomorphological studies seldom consider the impacts of the full range of processes, which can lead to planform change. However, case studies conducted at the reach-scale have provided

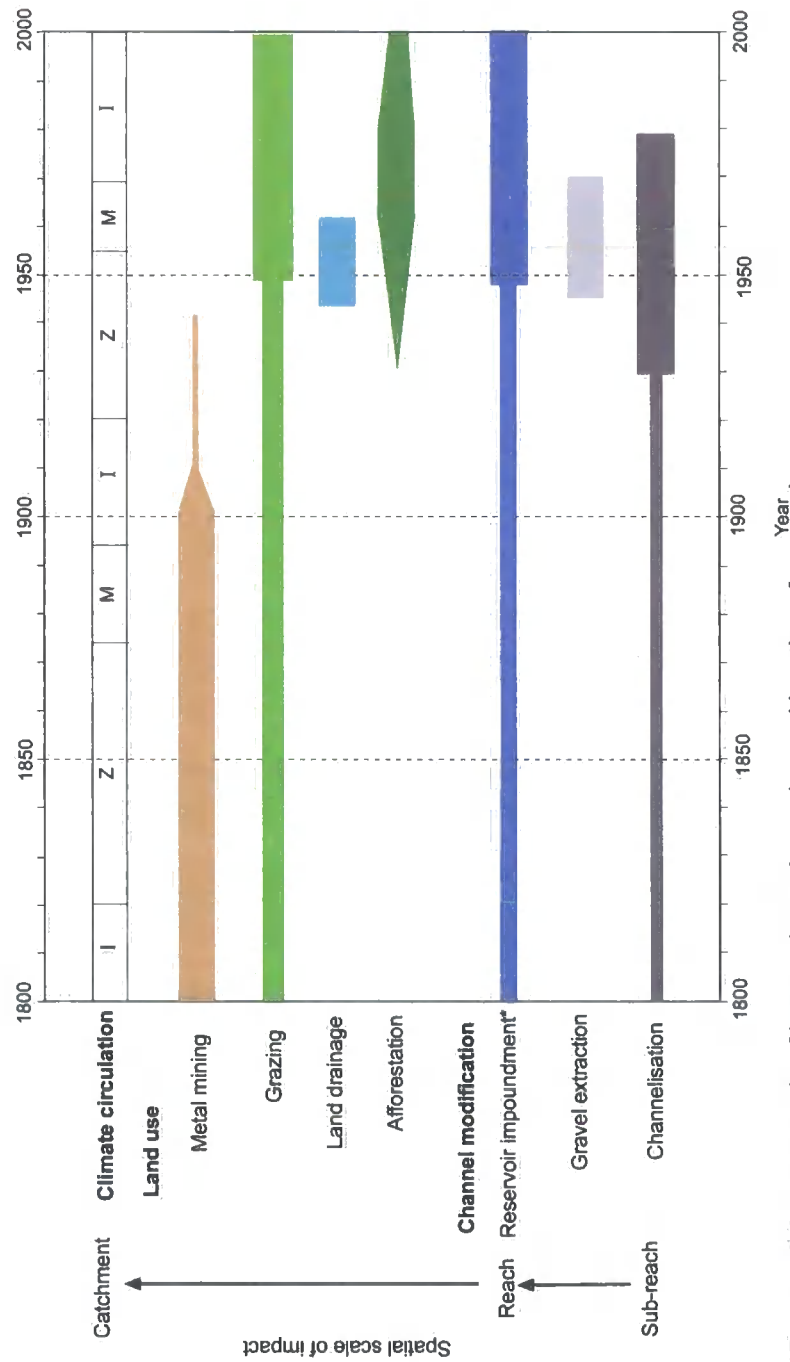
insights into the significance of a whole suite of processes. Assessing the relative significance of combinations of processes presents a considerable challenge to fluvial geomorphology.

In an attempt to address this complexity the focus of geomorphological investigations are now shifting towards the consideration of whole catchments. Catchment wide appraisals enable a wide range of processes to be considered. Focussing on the historic past, catchment wide appraisals benefit from a range of quality data sources such as maps and aerial photographs, archival records such as flow series and historic accounts. Evaluating process interactions over the historic period within a regional context is beneficial, as the significance of differing rates of processes can be appreciated and spatial and temporal lags evaluated.

2.4 Conclusion

Channel planform change in the British uplands has been caused by a range of mechanisms. In general terms variations in discharge and sediment supply account for observed changes in channel planform. While these are principally driven by climatic conditions they are strongly influenced by catchment land use, anthropogenic channel modifications and geomorphological factors. To date research into upland channel planform change in Britain, particularly in the North Pennines, has emphasised the importance of climate-induced variations in flood frequency and catchment metal mining, although anthropogenic channel modification and the influence of prehistoric and historic forest clearance are acknowledged to be important. However the extent of channel modifications in particular remains to be fully evaluated. In addition, determining process dominance remains a significant challenge especially where multiple processes occur over varying time scales within the same catchments. Figure 2.6 provides a summary of the range of processes likely to have had an impact on river channel planform in upland catchments over the historic period. These are classified according to the spatial scale of their impacts and variations in their intensity over the last 200 years are shown. In order to fully appreciate the causes of channel planform change in British upland catchments, the full range of processes must be considered and their temporal and spatial variations explored. Combining a catchment scale analysis of planform change, with detailed reach based investigations will enable a better understanding of the causes of planform change in upland catchments to be achieved.

Figure 2.6 Summary diagram showing the spatial extent and temporal duration of the main catchment-scale controls on river channel planform in upland catchments. The relative significance of controls over time is indicated by bar thickness. This Figure is intended for illustrative purposes and bar thickness is not proportional.



Chapter 3 Study sites and methodology

3.1. Scope of chapter

The aim of this chapter is to outline the research methodology and introduce the study sites. Chapter two emphasised the importance of the distinction between single thread and wandering channel planforms, and revealed that changes between these two planforms have occurred widely in the British uplands. The mechanisms which are thought to control channel planform are both numerous and operate over a range of differing spatial and temporal scales. The research framework has been designed to consider processes operating over historic time over a range of spatial scales. Central to this however is the recognition that catchment structure may also influence channel behaviour, as is reflected in the choice of study sites and the approach adopted at each. Having established this framework the study catchments selected are then described in detail, including the geological, geomorphological and land use histories of the catchments. This provides the context for the historical and contemporary investigations undertaken. Finally the detailed methodological techniques used in each catchment are described, this includes the justification for technique selection.

3.2. Research framework

3.2.1 Developing an appropriate research framework

The recognition that potential channel planform controls operate over a range of spatial and temporal scales was a key consideration for the development of the research framework. The primary goal of this thesis is to enhance our understanding of how these influences interact to determine channel planform. Of particular importance are the nature of, and the connections between, different controlling factors within the catchment. In this context the downstream impact of disturbances is of particular significance, and is demonstrated by the variation in the nature of sediment transfers within catchments as a result of differing forcing mechanisms. Reach scale approaches have traditionally been the favoured spatial framework for historical and contemporary investigations into channel behaviour as these enable research to be conducted at high resolution. However such an approach is unsatisfactory if the connectivity between discrete sections of the catchment is to be examined.

The need to increase spatial scale from individual reaches to larger more continuous sections of the channel network has long been recognised; for example Macklin and Lewin (1989) recorded changes in mean active gravel width of 500 m sections along the trunk channel of the South Tyne catchment (22 km). Despite the relative coarse sampling interval, this work established the significance of variations in sediment storage through space and time, and provided quantification of channel changes over a wide spatial scale. Elaborating on this, Macklin et al (1998) quantified channel changes along the entire trunk channel (85 km) of the River Tyne, for four time intervals between 1860 and 1975 by extending the common reach scale approach to reconstruct channel planform from archival sources allowing change over 115 years to be quantified. Specifically this involved digitising the river planform and determining changes in channel gravel area for 500 metre sections of channel. While this greatly enhanced the appreciation of the spatial variation of channel change and allowed quantification of channel change along the trunk channel, the technique was not extended to the tributary channels of the catchment. Brewer et al (2000) adopted a similar approach to determine changes in the extent of exposed riverine sediment (essentially gravel) along the trunk channels of eight rivers in Wales. This enabled the wider significance of channel changes to be evaluated, however such a programme of digitisation is labour intensive and the increase in spatial extent meant the temporal timescale was limited to the last 50 years. Changes in gravel area were quantified from aerial photographs taken in the late 1940s and in 1992. Again tributary streams were excluded from the analysis.

Extensive research approaches focusing on measuring change along the entire trunk channel of catchments neglect to examine the major tributary channels. Knowledge of tributary behaviour continues to be derived from local reach scale studies. This is a significant omission as not only do events in the tributary channels influence the behaviour of the trunk channel (through sediment transfer) but they have also been shown to be very sensitive to climate and land use change (Macklin, 1986; Macklin et al., 1992; Macklin et al., 1994). Importantly, understanding the behaviour of all major tributaries within the same catchment removes uncertainty about the representativeness of changes recorded along individual tributary channels. However, expanding the spatial scale of research results in significant logistical constraints, as reconstructing channel planform along long sections of channel is extremely time consuming (Macklin et al., 1998, Brewer et al., 2000). Increasing spatial coverage necessitates a reduction in the temporal scale of the results.

In this study a catchment scale approach has been developed which involves determining channel changes along both the trunk channel and major tributaries of the catchment over the past 150 years. Catchment scale investigations such as these involve the analysis of change along considerable lengths of river channel. Previous investigations have involved the digitisation of the river channel for each survey year (Macklin et al., 1998, Brewer et al., 2000). However such a wide spatial and temporal framework mitigates against the extraction of gravel areas from digitised reconstructions of channels for each survey year, instead the distribution of changes in gravel extent and associated changes in channel planform are classified and mapped (Section 3.4.2.1). This is considered to be appropriate because previous studies, at a variety of spatial scales, emphasise that the primary response of river channels to disturbance has been through changes in gravel bar extent. Changes in the spatial distributions of active gravel extent through space and time also provide insights into the source and transfer of coarse sediment through the catchment, allowing the cause of channel changes to be evaluated. Where sedimentation or gravel area changes are sufficient this will result in channel planform change. The changes in channel planform over the last 150 years are then classified and mapped. The detail of this is described in section 3.4.2.1.

Providing quantification of changes in gravel-bar extent is important for appreciating the relative significance of the changes in gravel bar area. This is particularly important along the trunk channel of the catchment where, as previous research suggests, channel changes may be substantial (Passmore et al., 1993). In the context of this study the extensive studies by Macklin et al. (1998) and Brewer et al. (2000) represent an intermediate scale between catchment and reach scale investigations. While providing useful quantification of changes in the extent of active gravel, a good indicator of sediment supply, these studies only provide an indirect quantification of channel planform structure and its change. For example knowing the change in extent of active gravel for 500 m intervals does not reveal the impact of this change on actual channel planform. Channel width data, however, such as those averaged for 500 m intervals by Macklin and Lewin, (1989), provide a better indication of the planform of the channel by giving an indication of channel width. In this study actual (as opposed to reach averaged) channel width data are recorded with a high sampling resolution, with active bars and vegetating bars subdivided. This enables both the change in gravel extent and planform structure to be derived. Usefully such an approach also enables change in the lateral extent of the channel to be quantified, including bank erosion and bar stabilisation. Such a measurement

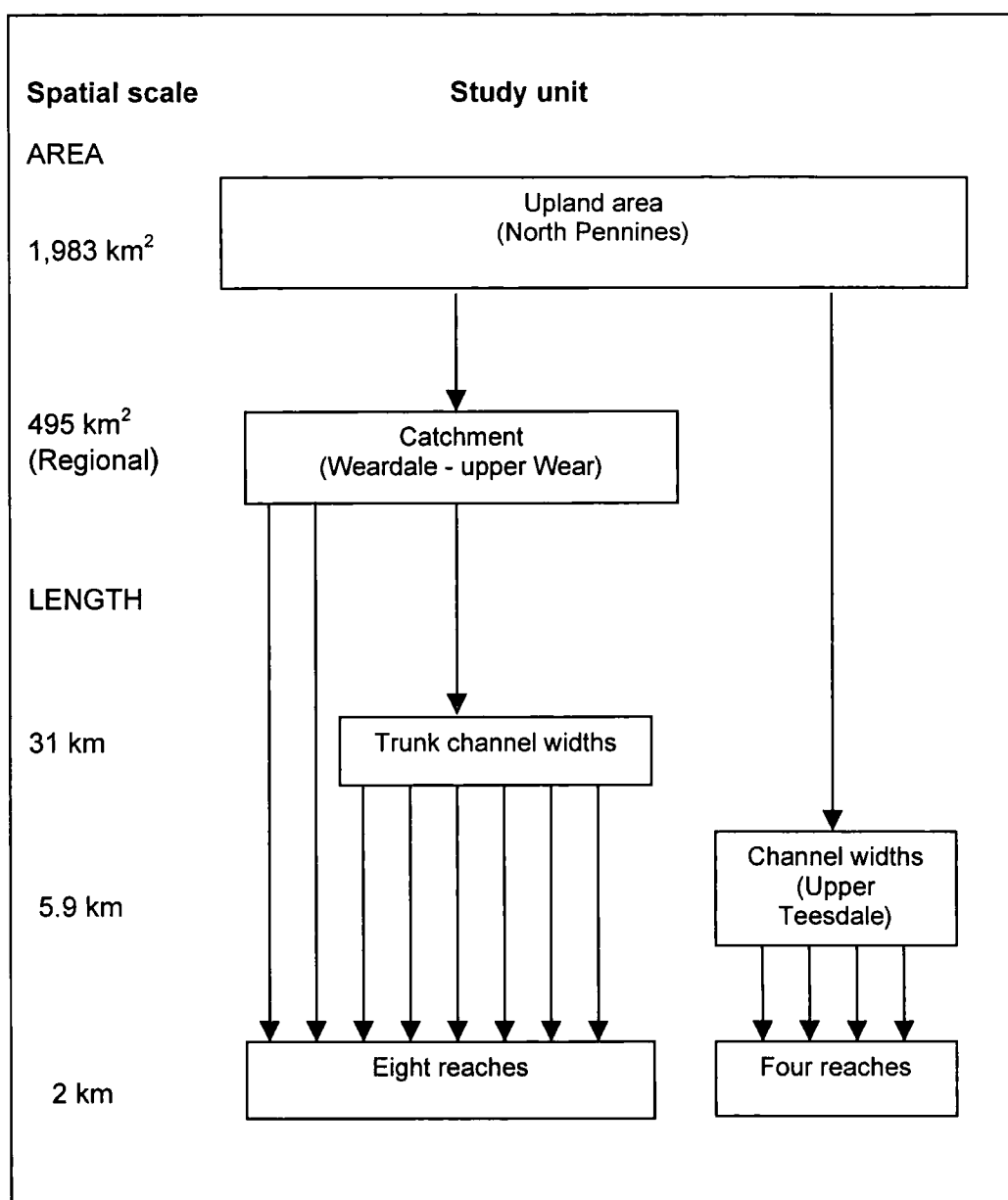
programme when applied to the entire trunk channel of a catchment provides not only a good appreciation of the magnitude of changes in gravel extents but will also provide excellent channel planform detail over a wide spatial scale and allow comparisons with other studies.

Reach scale approaches remain desirable for two reasons, first they allow detailed reconstructions of channel planform change to be made for key sections of river channel and second they enable local influences to be evaluated. Changes in channel planform are determined by reconstructing planform for a given year from maps and aerial photographs. This enables change through time to be evaluated through a combination of direct visual appraisal and the quantification of planform change through changes in bar extent, which is more meaningful when used in conjunction with reconstructions of channel planform. In this study eight carefully located (widely distributed) reach scale investigations supplement the catchment scale and trunk channel investigations by providing additional quantification of channel changes. The location of these study reaches guided by the catchment scale analysis, specifically the classification of channel planform change, enables those reaches with substantial and/or persistent channel changes to be examined in detail.

3.2.2 Applying the research framework

The research framework described above represents a 'nested' research strategy. The catchment scale approach provides a regional appraisal of planform change at a relatively low resolution. The trunk channel width series analysis is nested within the catchment scale analysis, with a reduced spatial extent but greater channel resolution. Nested within these are the reach scale investigations. This three-tier research strategy has been applied to Weardale (Figure 3.1). Here a catchment scale reconnaissance exercise determines the distribution of channel changes throughout the catchment, specifically changes in gravel bar extent, between 1856 and 1991. Nested within this, trunk channel width structure was determined along 31 km of channel for the years 1856, 1896, 1951 and 1991. Nested within these analyses the eight widely distributed study reaches provide detailed channel planform reconstructions for the period 1841-1991. Significantly the reach scale analysis allowed the inclusion of some additional historical sources, such as plans and aerial photographs, which were not available for the entire catchment.

Figure 3.1 Schematic diagram illustrating the nested research framework.



For the companion study in upper Teesdale a two-tier research strategy was selected involving the determination of contemporary channel width structure for 5.9 km of the trunk channel of the catchment, within which four reach scale investigations were nested (Figure 3.1). Channel width measurements were made along the contemporary channel in order to investigate how this compared to the river channel in Weardale over the historic period. Reach investigations focused on the period between 1856 and 1991, however at two sites channel reconstructions were extended to 2002 to determine the impact of high magnitude floods on channel planform, following a large storm on the 31 July 2002. This approach was designed

both to establish the wider significance of the results from Weardale, and to evaluate the impact of catchment structure on planform change. The selection of upper Teesdale was made on the basis that the contemporary river channel is characterised by local channel division and recent changes in channel planform. Contemporary planform activity can provide insights into the nature and cause of historic channel planform change. The upper Teesdale catchment is smaller than Weardale, and is a sub-catchment of the upland catchment of the River Tees (Teesdale); the catchment is predominantly montane in character, in contrast to Weardale where only the upper reaches of the tributary streams lie in the montane zone (Section 3.3). It therefore provides a useful comparison with Weardale.

3.3 Study sites

3.3.1 Regional setting

Weardale and upper Teesdale are located in the North Pennines, an area of uplands running through the centre of northern England (Figure 3.2). While there is no universally accepted definition of an upland area, in Britain the uplands are often defined as land that lies above the 300 m contour. This represents around 30% of the land area of Britain (Atherden, 1992). Locally however, valley floors can lie below 300 m but being surrounded by land above 300 m and may be considered upland. In light of this a more acceptable lower elevation may be 240 m (Allaby, 1983). Figure 3.2 shows the distribution of upland areas in Britain. Given the considerable physical, climatological and ecological variation in the uplands it is necessary to sub-divide these areas. It is particularly important to distinguish upland areas from montane areas. Mountains are characterised by high elevation, steep or precipitous gradients, exposed bedrock and the common occurrence of snow and ice (Barsch and Caine, 1984). However such a description is inappropriate for much of the British uplands, with the exception of the Scottish Highlands. Ecological boundaries provide a useful framework for characterising the uplands as these reflect climatic changes with increasing altitude. Figure 3.3 summarises the zonation of upland habitats in Britain.

The sub-montane zone (300 m – 600 m) in the British uplands has been profoundly altered by human activities and the North Pennines are no exception. While woodland once extended to the tree line, deforestation has depleted this habitat. Grazing of cleared woodland creates areas of heath where dwarf shrubs such as heather dominate (Fielding and Haworth, 1999), and this is particularly common in

Figure 3.2 The distribution of upland environments within Britain and Ireland
(Modified from Fielding and Haworth, 1999, p 3)

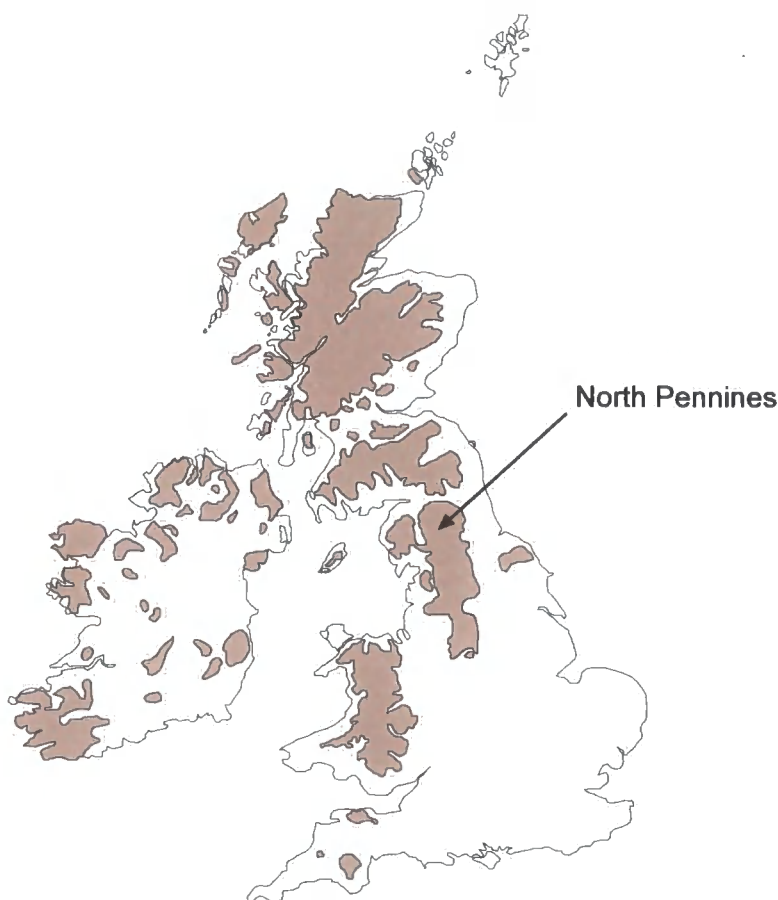
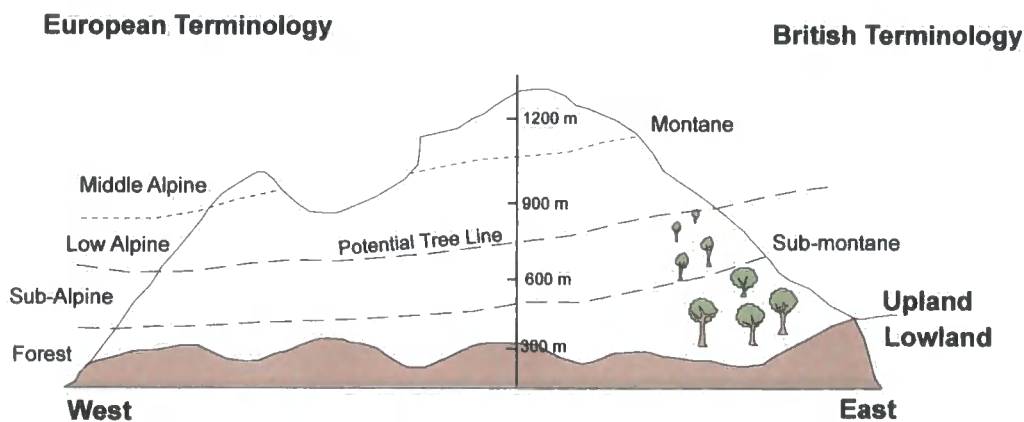


Figure 3.3 Zonation of the British uplands with reference to ecological boundaries.
(Modified from Fielding and Haworth, 1999, p 3)



the North Pennines. Extensive areas of mire occur in the British uplands. Three types of mire occur: fens, raised bogs and blanket mire. Of these, blanket mire is most extensive, covering 7.5% of the landmass of the British Isles (Tallis et al., 1997). The accumulation of blanket mire is thought to have begun in clearings within upland woodlands produced by hunter gathering communities during the Mesolithic (8.5-7.5 Ka B.P.), with more extensive growth induced by further woodland clearances by early farmers (Simmons, 1990). In the North Pennines the montane zone (above 600 m) is dominated by blanket mire, although as in other upland areas a range of other habitats are found locally: dwarf shrub heath, moss and lichen heath, grassland, mire, tall herbs and juniper and Willow scrub (Fielding and Haworth, 1999; English Nature, 2001). Aside from blanket mire however montane habitats are of very limited extent, in contrast with Scotland where more than 90% of this habitat is located (JNNC, 1995); the majority of the remainder is located in the Lake District Fells and Welsh mountains (Fielding and Haworth, 1999).

The morphology and thus setting of the river channels of British upland catchments, including the North Pennines, varies considerably due to unique combinations of geological, Quaternary glacial and periglacial legacy, climatic and anthropogenic influences (Newson, 1981). The degree of lateral confinement, slope-channel coupling and floodplain extent vary considerably depending on the nature of these influences. Newson (1981) argues that high rates of coarse sediment supply to rivers, due to a combination of steep climatological lapse rates and the legacy of Quaternary glaciation, make many British upland rivers montane in character. Newson (1981) divides upland rivers into mountain streams characterised by (1) steep channels and slopes, (2) no floodplain, (3) a flashy regime and (4) large-scale roughness elements; and piedmont streams with (1) a reduced channel gradient, (2) a well-developed floodplain and (3) channel processes dominated by storage and reworking of mountain sediments. The majority of studies focusing on upland channel planform change examine channels with an altitude of less than 600 m (sub-montane). Although piedmont channels are located at the margin of the uplands, they have many features in common with upland channels due to their high flow power, flashy regime and erodable banks.

3.3.2 Geological evolution of the North Pennines

The North Pennines can be divided into two structural blocks divided by the Stainmore gap, a topographic low formed by the Staindrop Fault (Figure 3.4). In the north the uplands are formed by the Alston Block and in the south by the Askrigg Block. Weardale and Moor House are both located within the Alston Block. The landscape of the North Pennines is strongly controlled by geology. This section considers the geological evolution of the Alston Block. The geology of the Alston Block is summarised in Figure 3.5 and the general structure illustrated in cross-section in Figure 3.6. Geologically the origin of the Alston block can be traced back to the late Silurian (425 Ma) (Figure 3.7).

The initial development of the Alston Block began with tectonic movements during the Caledonian Orogeny, of the late Silurian to early Devonian. This folded and fractured the Ordovician sediments of the Skiddaw Slates Group which form the basement rocks of the Alston Block (Taylor et al., 1971). At approximately 392 Ma, during the Devonian, a granite batholith (The Weardale Granite) was intruded into these sediments (Bott and Johnson, 1970). Intrusion of this granite batholith, of lower-density than surrounding strata, led to uplift, marking the beginnings of the Alston Block. Following a period of erosion during the Devonian (Dunham, 1990) differential subsidence during the early Carboniferous caused faulting around the structurally positive Alston Block forming a series of marginal sedimentary basins, such as the Northumberland and Stainmore Troughs, (Johnson et al., 1995).

Sedimentation began in these marginal basins as they were inundated by the sea. Subsequently during the Dinantian (Tournaisian), the Alston block also began to subside during a phase of regional crustal extension (Johnson et al., 1995). Following the deposition of marginal marine sediments, fully marine sedimentation on the Alston Block commenced during the early Dinantian (Figure 3.7). Cyclothemetic deposition of shallow marine carbonates, shallow marine shales and fluvial sandstones and massive limestones continued, forming the Lower Alston Group. In the late Dinantian rhythmic cyclothemetic deposition produced the Yoredale facies of the Upper Alston Group (Dunham, 1990). The following phase, the Namurian, began with the deposition of a thick limestone known as the Great Limestone. Following this, rhythmic alternations of shale, sand stone, coal and thin shelly limestones were deposited (Dunham, 1990). During the Namurian the marine influence declined and near-shore deltaic sediments became dominant forming the Millstone Grit Series

Figure 3.4 The regional structure of the Pennine Range

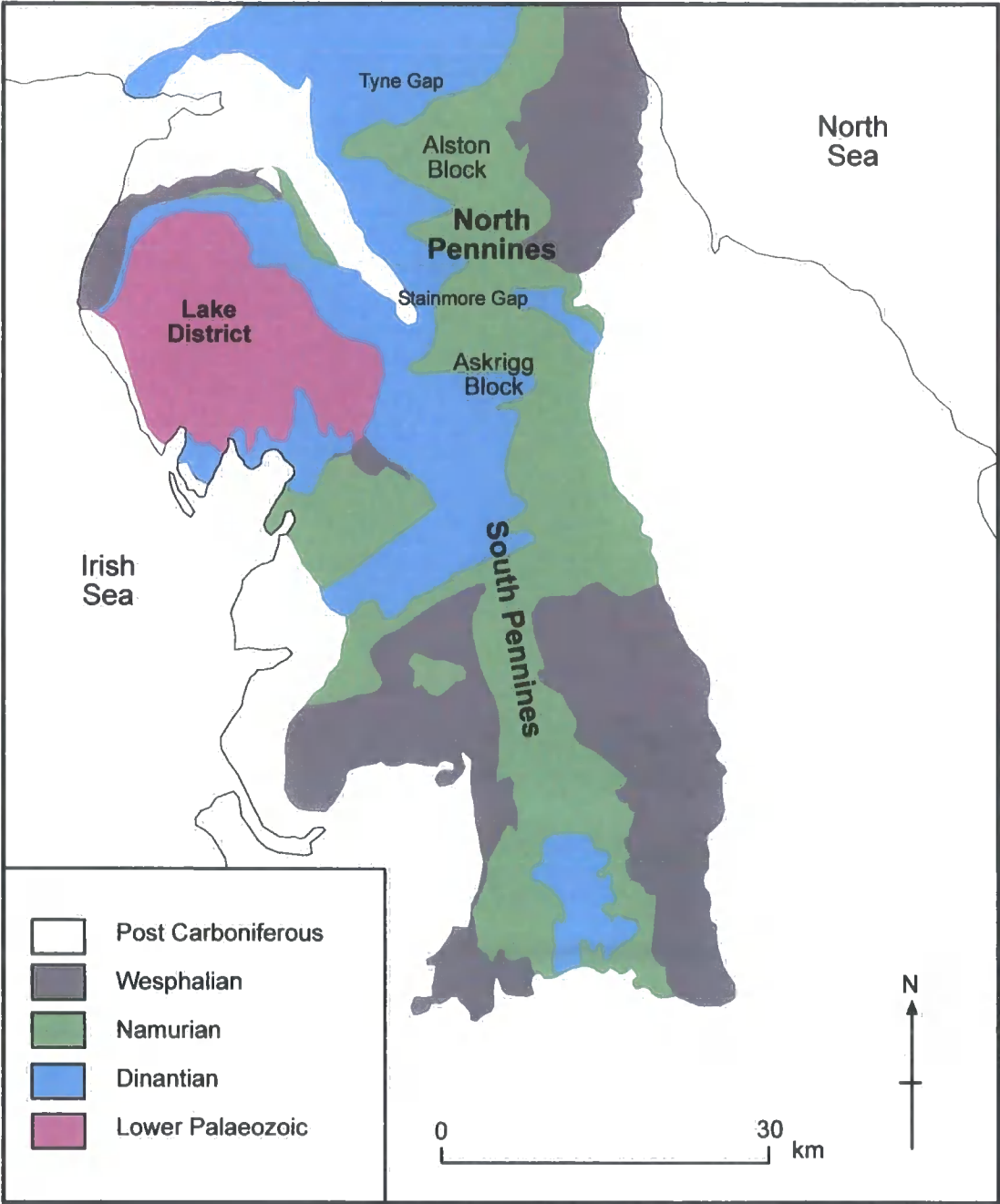


Figure 3.5 The geology of the Alston Block (Modified from Johnson, 1995 p235).

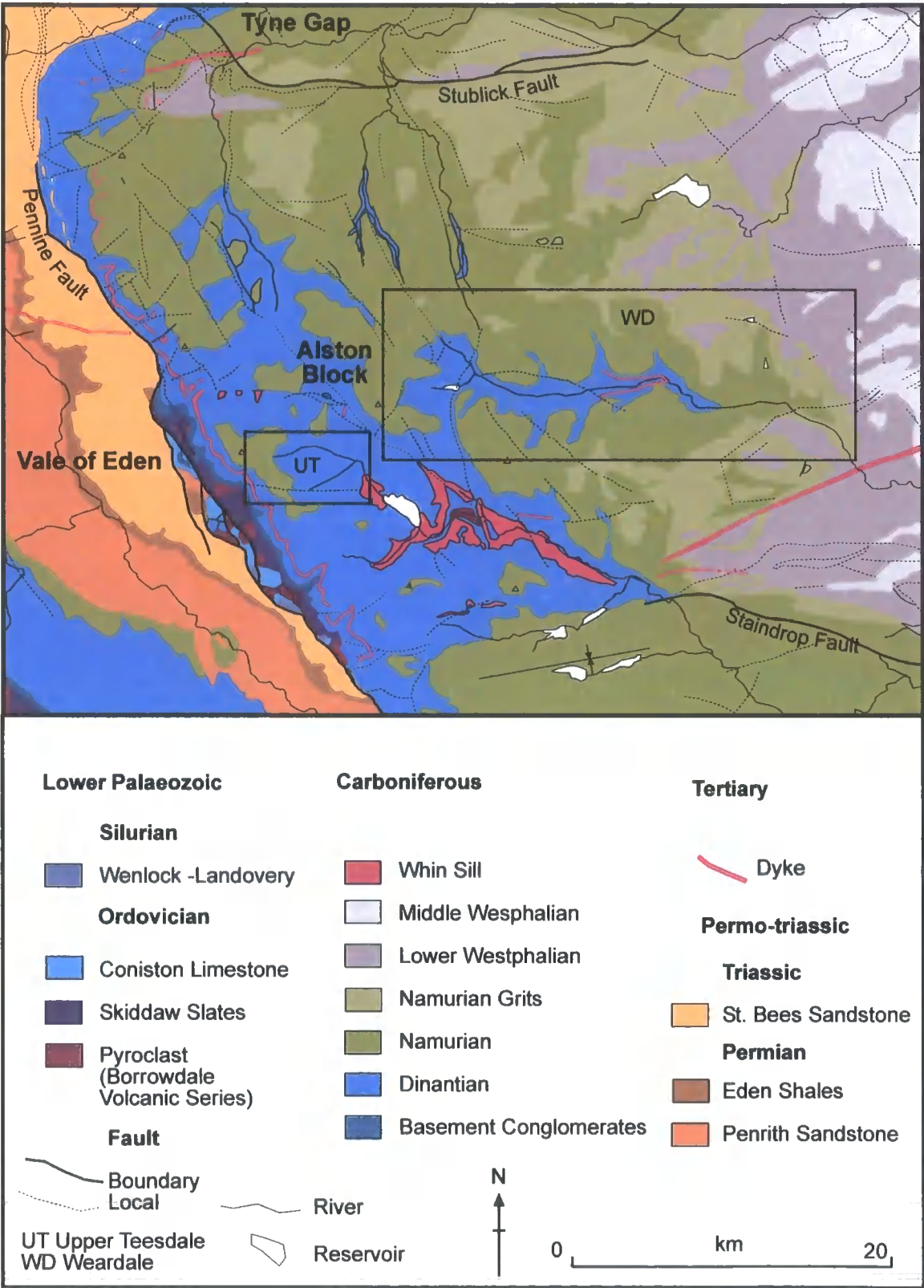


Figure 3.6 Geological cross-section of Northern England (Modified from Taylor et al., 1971, p9).

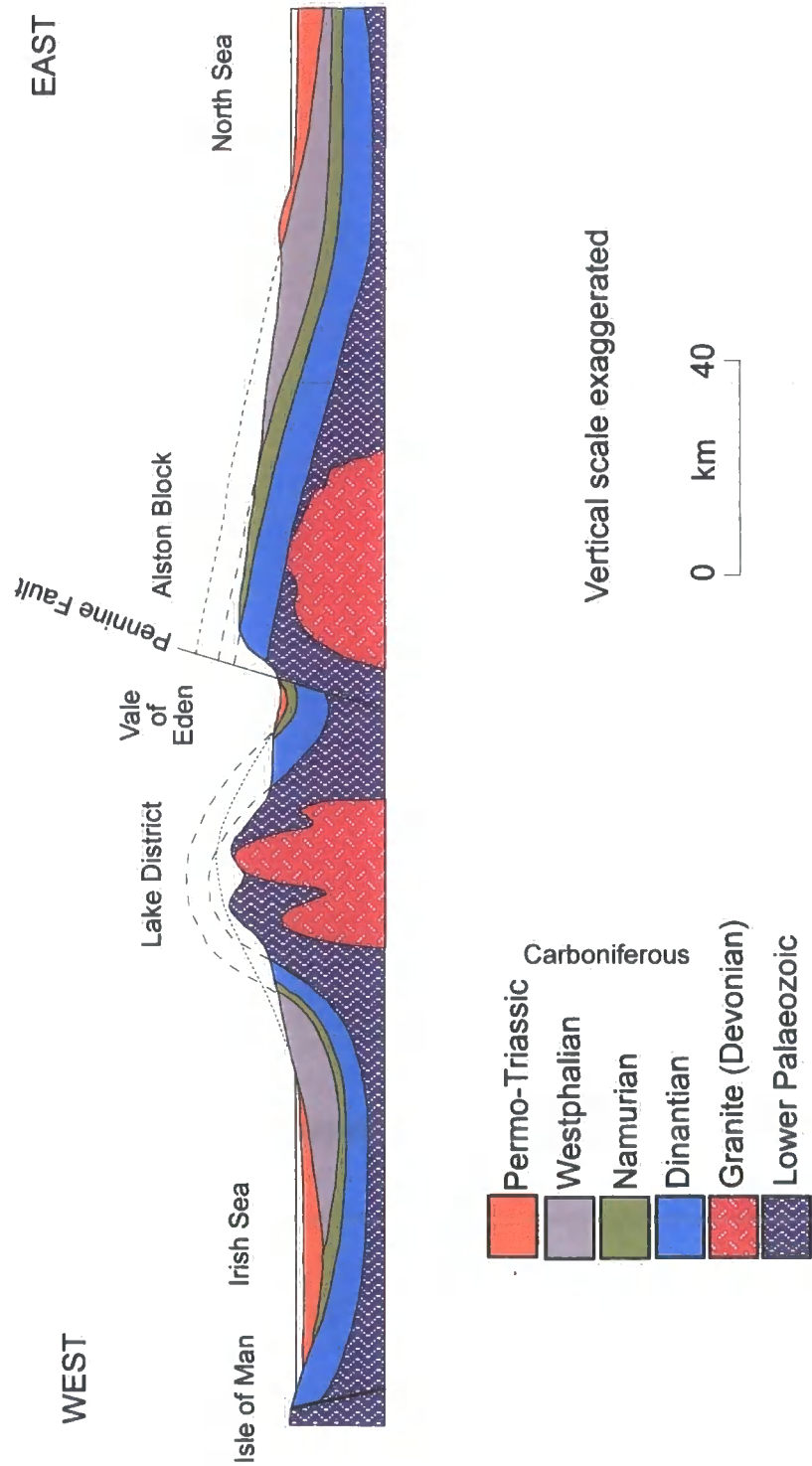
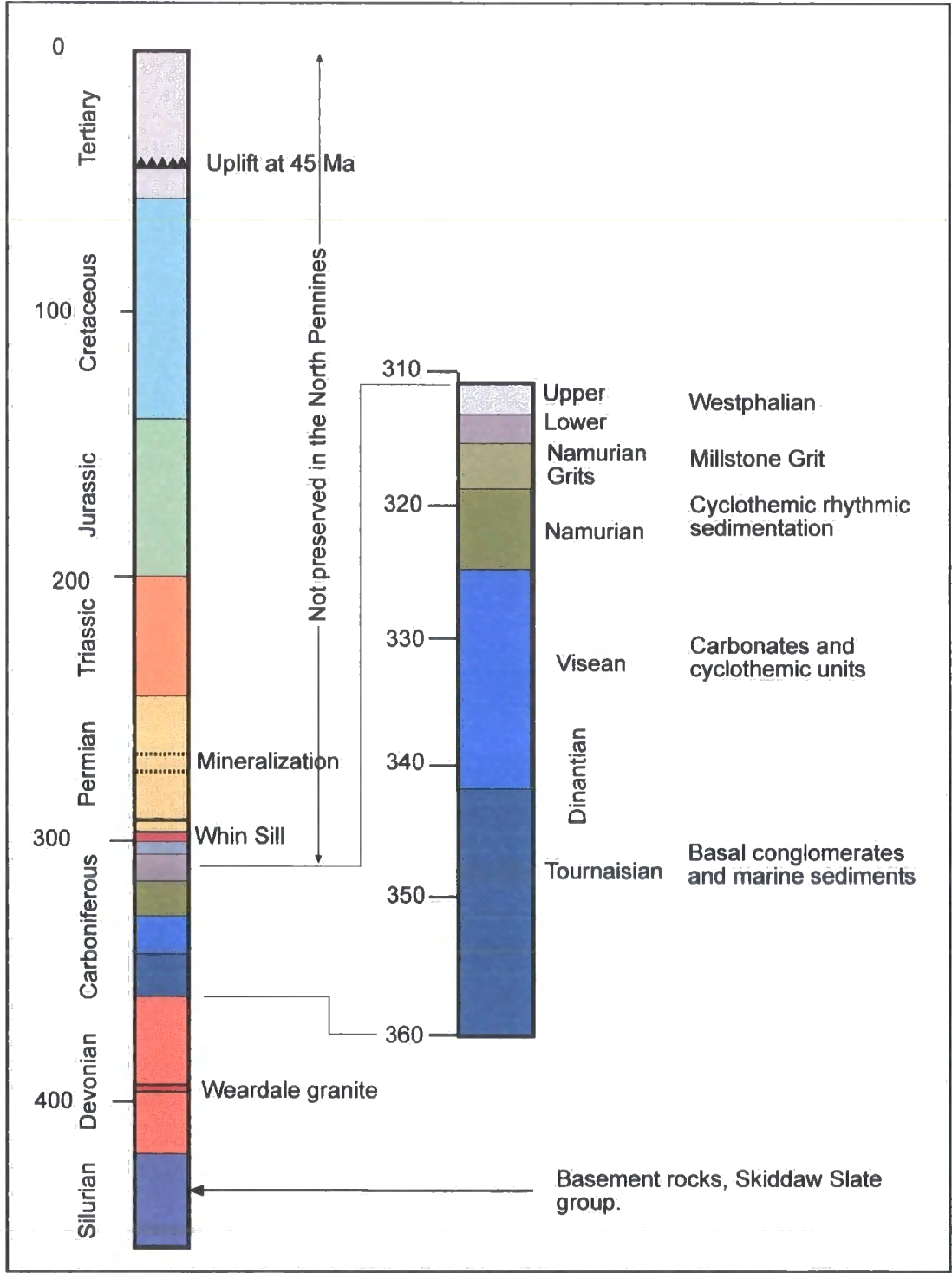


Figure 3.7 Summary of the key geological events in the development of the North Pennines. Time in millions of years before present.



(Johnson, 1970). This reduction in the influence of marine conditions continued into the Westphalian. The Westphalian rocks, collectively known as the coal measures, are characterised by cyclothem sequences of shell-beds, occasional marine horizons, shale, siltstone, sandstone, seat earth and coal seams all characteristic of deposition in periodically submerged deltaic, swampy environments (Johnson et al., 1995). The Westphalian is largely absent from the Alston Block being restricted its eastern margin (Figure 3.5).

The upper Westphalian in Northern England is truncated by an unconformity, possibly related to a compressional event near the Carboniferous-Permian boundary (Cann and Banks, 2001). This compressional event is marked both by Regional doming and the Burtreeford Disturbance, a monocline that extends across the Alston block. The Burtreeford disturbance is thought to have formed either contemporaneously or slightly earlier than the Whin Sill (Dunham, 1990). The Whin Sill Complex is a concordant intrusion of quartz-dolerite, which takes the form of a complex of sheet intrusions and dykes (Randall, 1995). The Sill is thought to have been intruded during the late Carboniferous-Early Permian (Dunham, 1990). The most extensive outcrops of Whin Sill in the Alston Block occur in Teesdale along the south bank of the River Tees. In Weardale however, a thin sill known as the Little Whin Sill outcrops near Stanhope (Figure 3.5). The intrusion of the Whin Sill was also coincident with a period of compressive folding and faulting within the Aston Block associated with the Hercynian Orogeny (Bott and Johnson, 1970).

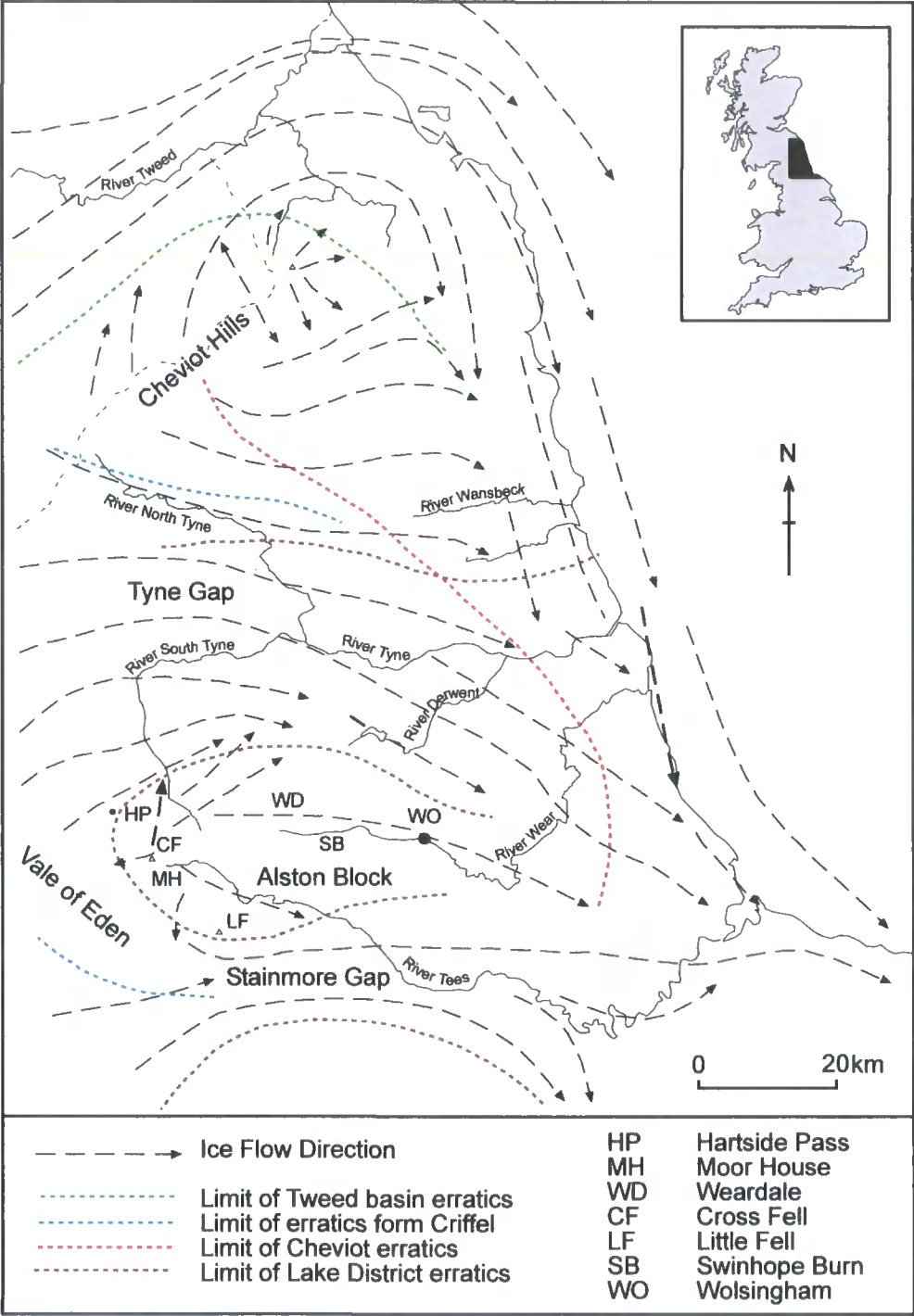
Extensive mineralization of the Carboniferous sediments occurred during the Upper Permian (Cann and Banks, 2001) forming the North Pennine Ore Field. These ores precipitated out of solutions moving through the bedrock (Dunham, 1970). Mineralization originated from at least four hydrothermal fluids. At least two of these fluids originated during the late Permian from the penetration of saline surface waters (Zechstein Sea) during crustal extension (Cann and Banks, 2001). At a depth of 10 km the solutions were heated to approximately 200°C and began to react with the surrounding rocks. This reaction with basement rocks is thought to account for the lead deposits in the Ore Field (Cann and Banks, 2001). Heat from the underlying granite batholith (300 °C), generated concentric zones of increasing fluid temperatures towards the granite. Additional hydrothermal fluids originating from surrounding basement rocks and neighbouring sedimentary basins are also thought to have contributed to the mineralization (Cann and Banks, 2001).

No Permian or Mesozoic deposits are found in the Alston Block, reflecting both hiatuses in deposition and also removal of deposits by erosion. Uplift of the Alston Block towards its present state of near isostatic equilibrium began during the Permian (Turner et al., 1995). Further uplift during the Tertiary reactivated major faults, particularly the Pennine Fault. Movement along the Pennine Fault resulted in the uplift of the lower Carboniferous strata above the Permo-Triassic sediments of the Eden Valley (Turner et al., 1995). Regional tilting of around 1° also occurred during the Tertiary (Bott and Johnson, 1970).

During the Quaternary northern Britain was repeatedly glaciated, however in the Alston Block evidence remains only of the last glacial phase of the Devensian, the Dimlington Stadial (Rose, 1985). During the Dimlington Stadial centres of regional ice dispersal developed in South Western Scotland, centred on Criffel, and the Lake District (Lunn, 1995). However the ice sheets generated in these areas failed to override the Alston Block (Raistrick, 1931). Ice in the Vale of Eden moving out from the Lake District was only able to cross the Pennine fault scarp north of the Hartside Pass and South of Little Fell (Lunn, 1995) (Figure 3.8). A local ice cap formed on the Alston Block centred on the Cross Fell and Wearhead areas (Moore, 1981). Ice on the Alston Block flowed in a southeasterly direction down Weardale and upper Teesdale, before becoming confluent with ice passing through the Tyne and Stainmore Gaps (Figure 3.8). During deglaciation landforms associated with melt-water movement including melt-water channels, kames and eskers formed near the margins of individual ice masses where these were formerly confluent. In the Alston Block area melt-water features are common in the Vale of Eden (Burgess and Wadge, 1974), in the area around Alston and in lower Teesdale (Lunn, 1995).

Despite climatic amelioration during the Windermere Interstadial, climatic deterioration marked a return to Arctic conditions during the Loch Lomond Stadial. With the exception of a small glacier beneath the escarpment at Cronkley Scar (Wilson and Clark, 1995), the Alston block area did not support ice cover. However, moraines identified in valleys of Middle Toun Beck, Knock Ore Gill (Johnson and Dunham, 1963) and in the headwaters of Maize Beck (Burgess and Wadge, 1974) have been cited as evidence of local glaciation during the Lateglacial. While glacial ice was virtually absent, periglacial activity produced block fields in the summit areas and solifluction lobes on hill slopes (Johnson and Dunham, 1963; Moore, 1994).

Figure 3.8 Ice flow patterns in northern England during the Dimlington Stadial
(Modified from Lunn, 1995, p301)

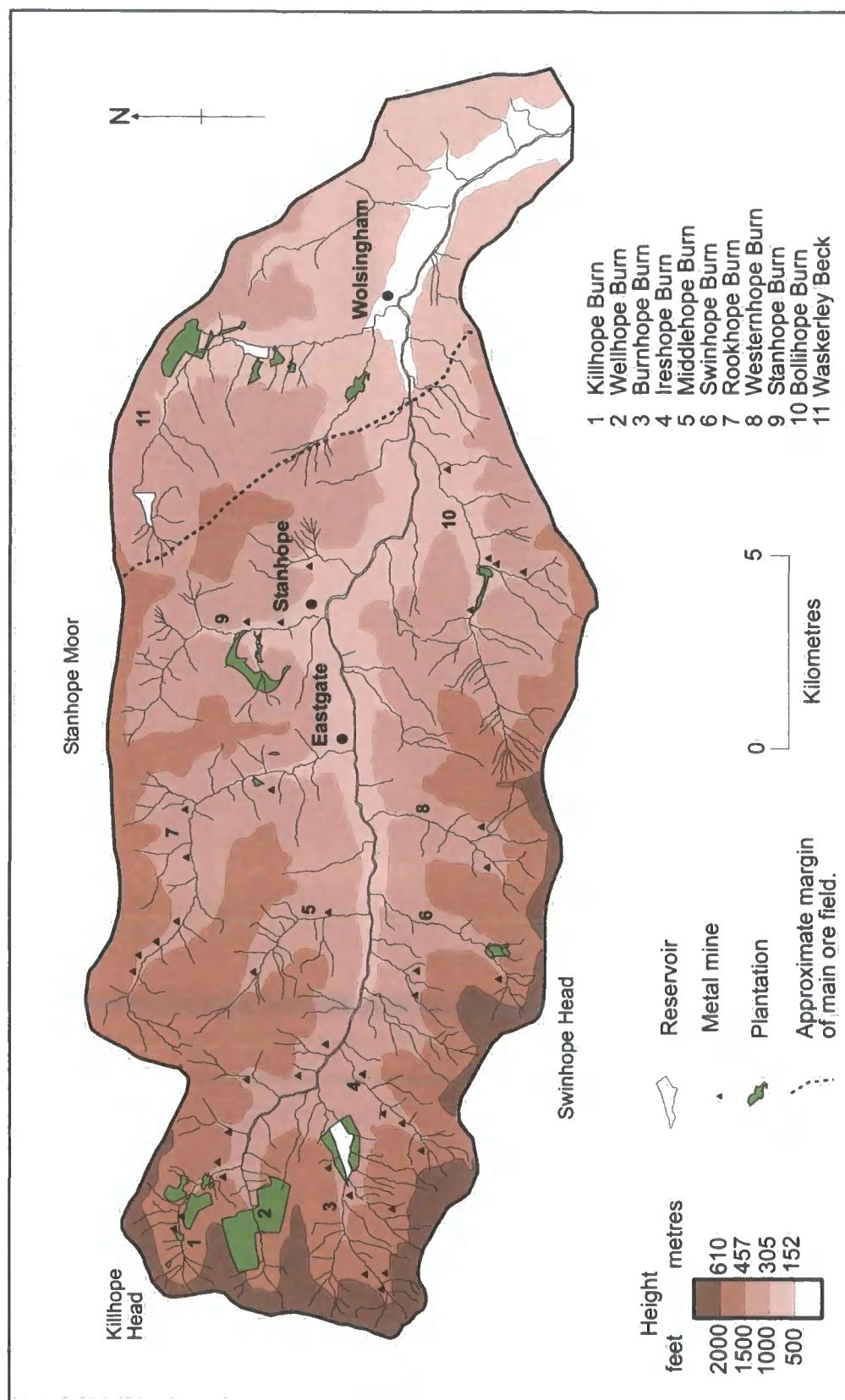


3.3.3 Weardale

Weardale is a west-east trending valley through which the headwaters of the River Wear drain the eastern flank of the Alston Block in the North Pennines (Figure 3.9). The headwaters of the catchment originate in the lower montane zone with a maximum altitude of 708 m. The annual rainfall is 875 mm and the vegetation is predominantly heather moorland. The larger tributaries of the River Wear descend through the sub-montane zone where land use is predominantly enclosed pasture and open moorland, before descending through narrow bedrock gorges into the main valley. The main valley floor of the dale is dominated by enclosed pasture, hay meadows and occasional arable land with localised conifer plantations.

Weardale is incised into the easterly dipping Carboniferous strata (Figure 3.5). In upper Weardale the valley floor and lower slopes are composed of Visean deposits while the upper slopes and summits consist of the overlying Namurian strata. Due to the easterly dip of the Carboniferous strata, in lower Weardale around Wolsingham, the dale is underlain entirely by Namurian bedrock. In the lower-most reaches of Weardale the upper valley sides are composed of Westphalian strata, which overlie the Namurian. Throughout much of Weardale the Carboniferous sequence is underlain by the Weardale Granite, a large granite batholith of Devonian Age (392 Ma BP) (Bott and Johnson, 1970). During the Dimlington Stadial the catchment was completely submerged beneath local ice flowing from the ice cap centred over the upper reaches of the dale (Moore, 1981). During de-glaciation ice initially retreated up the dale toward the head of Weardale, while surrounding valleys remained completely submerged by ice (Moore, 1994). However during a brief re-advance, glacial ice within the main valley pushed up a moraine into the ice-free valley of Swinhope Burn (Moore, 1994). Throughout deglaciation extensive sand and gravel outwash deposits accumulated within the main valley, the remains of which are preserved as two upper terraces, which occur discontinuously throughout the central valley (Moore, 1994). Episodic Holocene fluvial incision resulted in the formation of further discontinuous terraces (at a lower altitude) along the centre of the dale. The most complete sequence occurs at Wolsingham where two late glacial and three Holocene terraces occur along the River Wear (Moore, 1994).

Figure 3.9 Map of Weardale showing locations of major metal mines, plantations and reservoirs. Tributaries are numbered and named in the key.



During the early Holocene the legacy of glaciation influenced geomorphic processes due to the availability of unconsolidated sediments (c.f. Church and Ryder, 1972). Moore (1994) argues that braided rivers flowing across and reworking a sandur deposited by the decaying glaciers, deposited the upper terraces of the dale. The rate of geomorphological processes declined as vegetation colonisation progressed and by 7 ka BP mixed deciduous and pine woodland covered all but the most exposed summits (Warburton, 1998). The arrival of humans in Weardale during the Mesolithic marked the earliest anthropogenic influence. Woodland clearance during the Mesolithic took the form of small clearings initially for hunting and later, agriculture (Roberts et al., 1972). The accumulation of blanket mire is thought to have begun within these clearings, with more extensive mire growth associated with the expansion of these clearings for agriculture (Simmons, 1990). Continued occupation of the dale during the Iron Age is likely to have resulted in further deforestation (Roberts et al., 1972). Deforestation became more extensive during the Romano-British period; pollen evidence indicates this produced a landscape similar to present, which persisted for over a thousand years (Roberts et al., 1972). Following subsequent woodland regeneration a further period of woodland clearance was in progress by the twelfth century to provide land for farming and pasture. However periodic land abandonment occurred in more marginal areas during periods of economic recession, for example during the mid-fourteenth century (Roberts et al., 1972). By mediaeval times much of the dale formed the hunting forest of the Bishops Palatine of Durham (Dunham, 1990).

The earliest metal mining in the North Pennines began during Roman times (White, 1998), however the Beaumont Company established the majority of the mines in the dale between 1692 and 1882. The Weardale Lead Company succeeded the Beaumont Company in 1883 and continued to extract lead. Iron mining, practiced in the Weardale since the Iron Age became more systematic with the foundation of the Weardale Iron Company in 1842. Both the Weardale Lead Company and the Weardale Iron Company began extracting fluorspar during the late nineteenth century (Dunham, 1990). Mining in Weardale was widespread during the late nineteenth century (Raistrick and Jennings, 1965) and peaked in the early twentieth century when over 100 mines were in operation (Dunham, 1990). Metal mining has profoundly influenced the landscape within the mineralised zone. Hushing has resulted in numerous linear scars along valley sides in the upper dale, which trace the course of former streams. Additionally a network of watercourses connects many

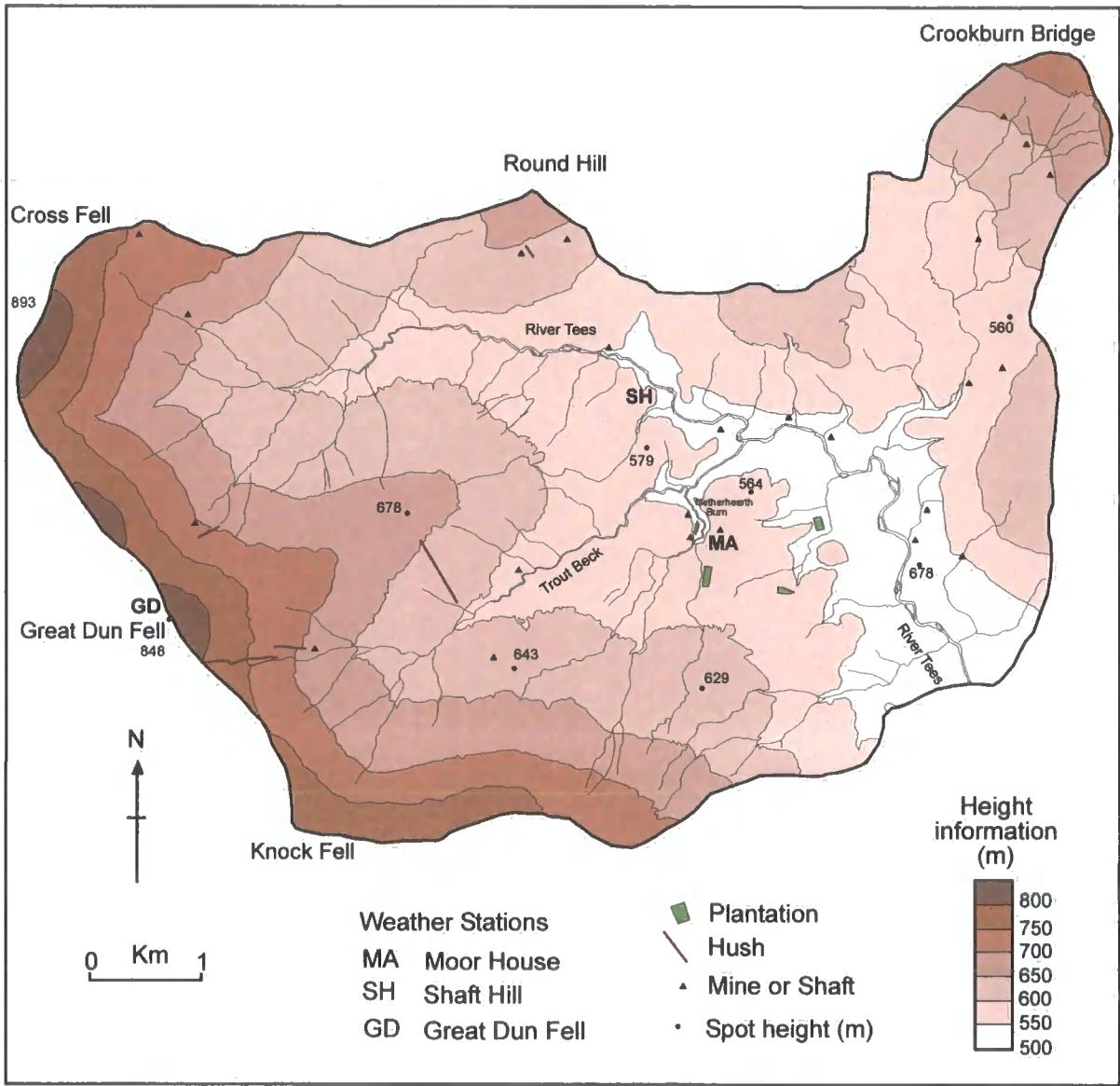
of the tributary streams, and at mine locations shafts, ruins and spoil heaps are numerous. Iron and lead production ceased by 1948, however fluorspar production, involving the reworking of mining waste, continued to grow although focusing on far fewer mines. Limestone quarrying in Weardale has been practiced since the 13th century. Extensive quarrying was carried out between Frosterley and Stanhope exploiting the Great Limestone of the lower Namurian. Some 22 km of quarry face has been worked in this area (Dunham, 1990) with several quarries located close to stream channels, such as along Bollihope Burn. During the later half of the Twentieth century piecemeal and large scale commercial gravel extraction operations were carried out in the dale (Newton, 1971).

3.3.4 Upper Teesdale

The upper catchment of the River Tees above Cow Green Reservoir in upper Teesdale lies to the east of Cross Fell and to the north of Dufton Fell (Figure 3.10). Ranging in elevation from 500 m to 893 m the catchment lies at the interface between the upper sub-montane and montane zones. The climate is sub-arctic oceanic with mean annual rainfall of 2010 mm (Smithson, 1985). The catchment is extensively covered by blanket peat, with a maximum thickness of 4 m, of which approximately 17 per cent is eroded (Garnett and Adamson, 1997). Dendritic gullying dominates on lower slope angles with linear gullies on steeper slopes (Evans and Warburton, 2001). Approximately 10 per cent of this eroded peat has re-vegetated (Garnett and Adamson, 1997). Blanket mire is absent along valley floors, here over-bank deposits of sands and silts overlie coarse channel deposits, and soils developed upon this deposits are highly organic.

Geologically the catchment is composed of Visean and Namurian strata. Visean strata, consisting of alternating limestone and shale beds with occasional sandstones, dominates below 700 m. Above this Namurian strata forms the high ground of Cross Fell, Little Dun Fell and Great Dun Fell (Figure 3.2). In the lower reaches of the catchment between High Crag Foot and Cow Green Reservoir the valley floor is underlain by the Whin Sill, which outcrops extensively in the bed and banks of the River Tees at this point. The bedrock in upper Teesdale is mineralised and the mineral veins have a general northeast – southwest trend. Clusters of veins occur immediately to the south of the summit of Great Dunn Fell and along the River Tees for one kilometre above and below its confluence with Trout Beck.

Figure 3.10 The upper Teesdale catchment, indicating locations referred to in the text.



During the Dimlington Stadial upper Teesdale was covered by a local ice cap, from which ice flowed in a south-easterly direction into the main valley of Teesdale (Figure 3.8). Till overlies bedrock extensively below 600 m. Much of this till was reworked by periglacial activity, primarily solifluction, during deglaciation and the Loch Lomond Stadial; this is thought to be responsible for the removal of drift from the ground above 600 m (Johnson and Dunham, 1963). Holocene river terraces occur discontinuously in the catchment, however with the exception of some low terraces along Trout Beck upstream of its confluence with Netherhearth Burn, these are restricted to the Tees valley below Trout Beck Foot. Little work has been conducted on these river terraces and their age remains uncertain.

The early Holocene land use history of upper Teesdale is similar to that of Weardale. The majority of the catchment below 700 m was wooded by 7 ka BP. The arrival of hunter-gatherer societies in the catchment during the Mesolithic is indicated by flints, which have been found at altitudes of up to 686 m (Roberts, 1978). Pollen evidence indicates that initially patchy Mesolithic woodland clearance on the Fells became extensive during the late Bronze Age and Iron Age. Despite limited woodland recovery during the Roman period, population growth during subsequent centuries saw continued clearance on the Fells (Roberts, 1978). It is likely that in the years prior to 1100 AD the catchment was used to graze livestock from isolated farms. By 1100 AD Norman lords had placed upper Teesdale under forest law preserving the area for hunting purposes. The high Fells continued to be used for livestock rearing between 1100 to 1600, although declining in intensity after 1300 following climatic deterioration (Roberts, 1978). The majority of the catchment located to the south and west of the River Tees now forms the Moor House National Nature Reserve with land use limited to limited grazing by sheep and occasional conifer plantations.

Lead mining in upper Teesdale began during the mid-sixteenth century and intensified with the arrival of the London Lead Company in 1692, which operated until 1905 (Johnson and Dunham, 1963). Metal mining involved both subsurface excavations and surface excavations (hushing). Several hushes were worked in upper Teesdale, both relatively small late 17th century prospecting hushes and larger 18th century hushes along veins (Johnson and Dunham, 1963).

3.4. Data collection and analysis

3.4.1. Archival data sources

The river channel planform information for Weardale required for each of the three scales of analysis was reconstructed from historic maps and aerial photographs. Additional ground truthing information was collected in the field where necessary. In upper Teesdale historical sources were used for the reach-scale channel reconstructions. The use of historical plans, maps and aerial photographs is common practice when reconstructing historic changes in river channel planform (Hooke and Redmond, 1989b). A number of criticisms have been levelled against the use of historic cartographic sources. First, maps only provide a snapshot of channel planform, and river channel behaviour must be inferred between surveys. As a result, determining the role of individual events can be problematic (Hooke and Redmond, 1989b). However, field evidence and historical flood records can provide an indication of events between map surveys. It is often suggested that maps are sensitive to variations in flow stage and apparent planform change may simply reflect this (Archer, pers com). However, surveys would have taken longer than a single flow event (rapid stage rise and fall in upland catchments), and were unlikely to have been conducted during high flow stage (bad weather). In addition, when maps are compared for differing sites and for the same site for differing years, the level of detail is highly consistent. These criticisms are more than offset by the advantage offered by their use. Historic maps provide otherwise unavailable detail of river channel planform extending through historic time (150 years or more) giving a unique appreciation of long-term river channel behaviour.

A range of cartographic sources that can provide channel planform information are available for British rivers (Table 3.1). Several historical maps spanning 150 years were available for Weardale and Teesdale. In general maps are suitable for planform reconstructions if riverbanks and gravel bars are depicted, as this ensures detail is comparable with the aerial photographs. However the spatial coverage of individual cartographic sources is variable. While some data sources are available for the entire northern Pennines, others were restricted to individual catchments or even specific locations within each catchment. Investigations of planform change throughout an entire catchment require full coverage by each source. Reach scale investigations, however, can be supplemented by additional data sources.

Table 3.1 Historical cartographic sources for Britain (modified from Hooke and Redmond, 1989b, p 82).

Cartographic Source	Date	Scale	Coverage	Accuracy
Estate Plans	Some late C 16 th Majority 1700 onwards	Typically 1:2 376	England and Scotland	Variable
Enclosure plans	C18 th and C 19 th	~1:10 000	England and Wales	Variable
Deposited plans	1794 onwards	1:15 840	Britain	Variable
County plans	C18 th and C19 th	1:63 360 1:31 680	England and Wales	Variable
Military Survey of Scotland	1774-1755	1:36 000	Scotland	Reasonably Accurate
Tithe	1840s	Typically 1:2 376 or 1:4 752	_ of England and Wales	Variable
Ordnance survey (Old series) Ordnance Survey (New Series)	1795-1873	1" = 1 mile 1:63 360	England and Wales	Poor
2 nd edition	1840-1893	All	England and Wales	Moderate
3 rd edition	1901-1913	1" = 1 mile		
4 th edition	1913-1926			
Ordnance survey (County Series)		All	England and Wales	Good
1 st edition	1853-1893	1:10 560 or		
2 nd edition	1891-1914	1:2 500		
3 rd edition	1904-1923			
4 th edition	1939			
National Grid Series	1948-1978	1:10 560 1:10 000 post 1969	Britain	Good

In addition, aerial photograph coverage was available for the mid to late twentieth century (Table 3.2). Stage differences are likely to be insignificant as flights are only made during periods of good weather conditions (clear visibility); the rapid rise and fall of flow stage means the channels are unlikely to be at high stage. Vegetation cover can be problematic both as it obscures channel detail but also as its extent varies seasonally. The extent of gravel bar vegetation is therefore influenced both by

the frequency of inundation, and the season. Seasonal effects can be accounted for, because the precise date of each photograph is known. Careful ground-truthing minimises such uncertainties for recent surveys, however early surveys may be more problematic. In addition care must be taken when comparing colour and black and white aerial photographs. While colour may enable subtle difference in vegetation cover and submergence by shallow water to be detected, these are often extremely difficult to detect using black and white photographs. Despite these limitations aerial photographs enable highly detailed reconstructions of channel planform.

The availability of archival sources is primarily dictated by the location of the study reaches within the catchment. Reaches close to the upland margin near settlements tend to have better cartographic coverage than isolated upland reaches. The range of archival sources available for Weardale and upper Teesdale have been summarised in Tables 3.3 and 3.4. The earliest available cartographic data for the North Pennines is provided by a series of Enclosure plans. Enclosure plans represent an early national land inventory; enclosure plan production was most significant during the eighteenth and nineteenth centuries (Hooke and Kain, 1982). Only 33% of enclosure plans produced prior to 1770 survive, whereas over 90% of plans produced since 1810 survive (Delano-Smith and Kain, 1999). In Weardale availability of these plans was restricted to the tributary streams of the southern side of Weardale and no coverage was available for upper Teesdale. Similarly a series of plans produced in 1844 for the construction of a railway line in Weardale provide only local coverage. These plans provide good planform and gravel bar detail where the railway was to be constructed in close proximity to the river and despite some minor generalisations resolution is consistent with the first edition Ordnance Survey map. As the accuracy of this plan is restricted to the immediate vicinity of the proposed railway, the plan is only useful locally along the trunk channel of the river.

The first extensive survey in the North Pennines is provided by a series of tithe plans spanning the period between 1839 and 1844. Tithe plans were designed to provide a national land inventory of enclosed land following the Tithe Commutation Act of 1836 (Delano-Smith and Kain, 1999). Being restricted to enclosed land, tithe plan data is often absent for high moorland areas as is the case in upper Teesdale. The quality of tithe plans is highly variable (Hooke and Redmond, 1989b) and they were produced at various scales and dates (Delano-Smith and Kain, 1999). In Weardale tithe plan coverage is extensive, encompassing the entire trunk channels and each major tributary stream. Comparison with the first edition Ordnance Survey maps of

Weardale suggests that planform depiction is slightly generalised, and has an error consistent with the general tithe plan planimetric error of 3-4 per cent (Hooke and Perry, 1976). A significant limitation of the tithe plans is that they do not always depict gravel bars and in more remote locations channel planform can become generalised.

Table 3.2 Maps and aerial photographs available for Weardale.

Description	Date of survey	Scale
Maps and Plans		
Enclosure Plan	1815	<i>Approx 1:2500</i>
Tithe Plan	1839	<i>1:2376</i>
Railway Plan	1844	<i>Approx 1:10 000</i>
First Edition County Series Ordnance Survey Map	1856-8	1:2500
		1:10 560
Second Edition County Series Ordnance Survey Map	1895-6	1:2500
		1:10 560
Third Edition County Series Ordnance Survey Map	1919	1:2500
		1:10 560
Fourth Edition County Series Ordnance Survey Map	1939	1:2500
		1:10 560
National Grid Series Ordnance Survey Map	1953	1:10 560
Revised National Grid Series Ordnance Survey Map	1976-78	1:2500
		1:10 000
Aerial Photographs		
MOD – RAF	1948	1:10 000
MOD – RAF	1951	1:10 000
MOD – RAF	1957	1:10 000
BKS Surveys	1971	1:10 000
ADAS	1986	1:10 000
Aerofilms	1991	1:10 000

Table 3.3 Maps and aerial photographs available for upper Teesdale.

Description	Date of survey	Scale
Maps and Plans		
First Edition County Series Ordnance Survey Map	1858	1:10 560
Second Edition County Series Ordnance Survey Map	1895	1:10 560
Third Edition County Series Ordnance Survey Map	1919	1:10 560
Revised National Grid Series Ordnance Survey Map	1976-78	1:10 000
Aerial Photographs		
MOD – RAF	1951	1:10 000
MOD – RAF	1953	1:10 000
MOD – RAF	1969	1:10 000
<i>Unknown</i>	1975	1:10 000
NERC	1991	1:10 000
NERC	1995	1:10 000
NERC	1997	1:10 000

A range of Ordnance Survey maps were produced during the nineteenth century (Table 3.2), of which the County Series provide the most useful cartographic data. The Ordnance Survey County Series map editions at 1:10560 and 1:2500 scale (surveyed 1858, 1895, 1919) provide excellent quality cartographic data for Weardale. This map series is considered to have an accuracy of $\pm 1\text{m}$ (Hooke and Redmond, 1989b). Additionally these maps depict both lateral and medial gravel bars distinguishing between bare gravel and semi-vegetated gravel bars. This makes these maps extremely useful sources of planform detail. Potential errors between maps due to differing river stage during survey (Passmore et al., 1993) are minimal as gravel bar areas and degree of detail shown are consistent between surveys. Incomplete fourth edition (1939) coverage is also available for sections of the lower reaches of Weardale, however a lack of coverage in the upper dale prevented the use of these plans. The National Grid Series Provisional Edition maps (1953) for this area were only partially revised from the third edition maps and the channel data is inconsistent between sheets, for this reason this source was disregarded. Channel detail on the 1:10,000 and 1:2,500 Ordnance Survey maps produced during the 1970's was found to be over simplified, Passmore et al. (1993) also found this to be the case. In upper Teesdale however, the first three Ordnance Survey map editions were only surveyed at 1: 10,560 and no fourth edition or National Grid Edition maps were available.

A wide-range of aerial photographs are available dating from the late 1940's onwards (Tables 3.2. and 3.3). Photographs taken of Weardale and upper Teesdale however were taken during different surveys. As such the dates of photography are different for the two catchments. In Weardale several photograph years have incomplete coverage and derivation of planform data was restricted to the 1951, 1971 and 1991 photographs as these provide the most extensive coverage of the dale. Similar problems were encountered in upper Teesdale where only the 1975 and 1995 photographs provide complete coverage of the catchment.

In summary three historical Ordnance Survey map editions provided sufficient cartographic quality and spatial coverage for the catchment scale investigations; these were the first (1856-8), second (1895-6) and third (1919) edition County Series maps. Two aerial photograph surveys were also available with sufficient spatial coverage; the 1951 RAF survey and the 1991 Aerofilms survey. For some reach scale investigations the Railway and Tithe Plans were used as were the 1957 and 1971 aerial photographs. In upper Teesdale planform reconstructions at the reach

scale utilised the first three Ordnance Survey maps (1858, 1895, 1919) and a range of aerial photographs (1951, 1953, 1969, 1975, 1995), although the 1951 and 1969 photographs were only available for certain sites.

3.4.2. Investigations conducted in Weardale

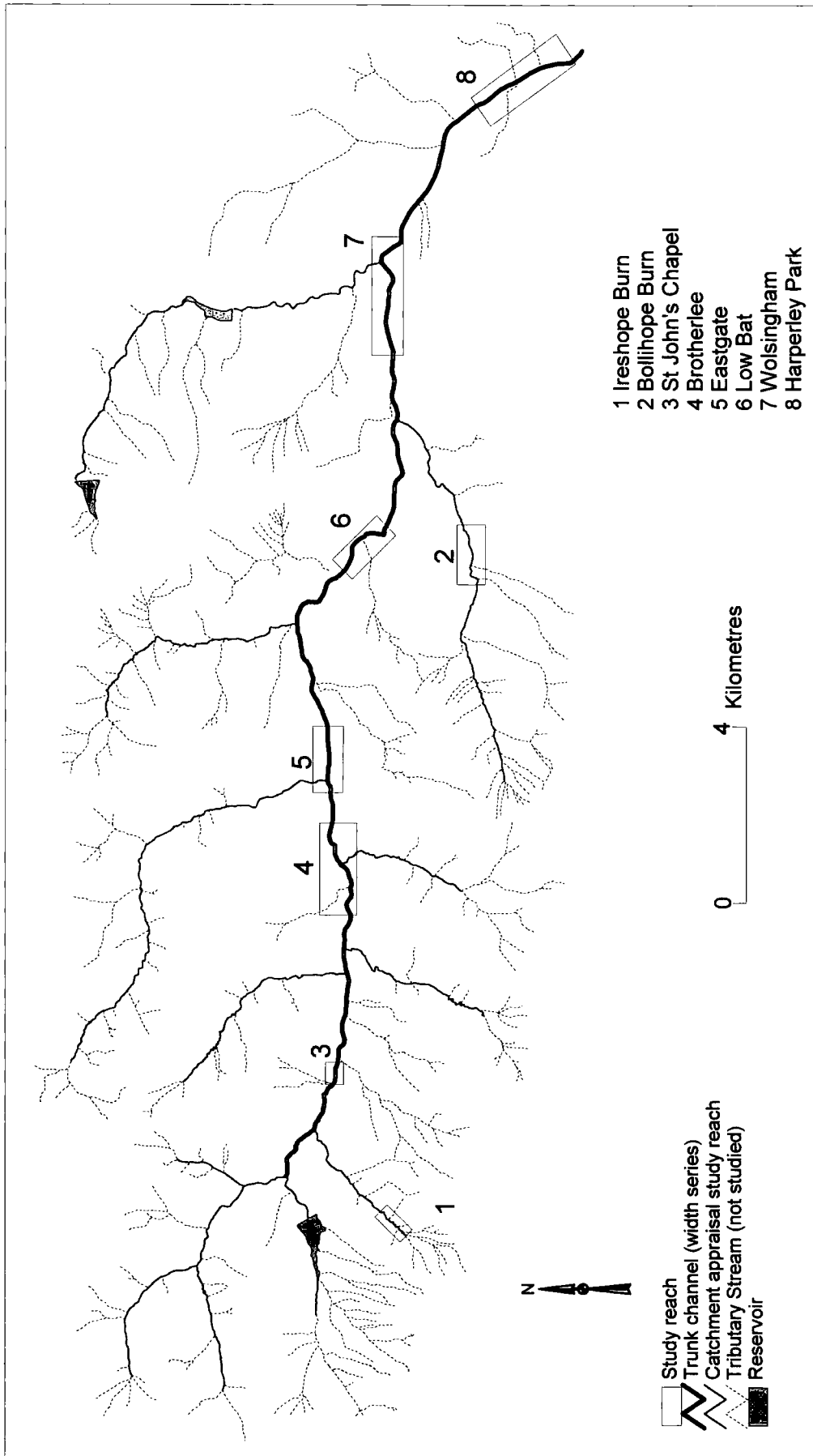
As described in section 3.2 the investigations conducted in Weardale were conducted at three spatial scales (Figure 3.1). The distribution of the study reaches for each of these spatial scales is outlined in Figure 3.11. As the analysis required the historical maps to show both banks of a channel together with gravel bars, only the larger tributary streams of the catchment were selected for analysis, smaller channels were often depicted as single lines. In some instances the depiction of minor tributaries with both banks appeared over simplified, as often bars were not included. These too were excluded from the analysis. The specific methodology applied at each of these scales is discussed in turn.

3.4.2.1. Catchment scale appraisal of channel change

The catchment scale investigations consisted of three elements. First the distribution of changes in gravel bar extent was mapped throughout the trunk channel and major tributary channels of the catchment for the periods 1856-1896, 1896-1919, 1919-1951 and 1951-1991. These dates were determined by the available archival sources. In order to provide a consistent catchment scale appraisal of channel planform change only archival sources that depict gravel bars and have total catchment coverage were examined. In Weardale this represented five sources; maps dating to 1856, 1896 and 1919 together with aerial photographs from 1951 and 1991. The tithe plan was excluded from the analysis, because it does not depict gravel bars.

As described in section 3.2, many large-scale studies into channel planform change have involved the direct digitisation of extensive lengths of river channel from which quantitative indicators of channel change could be made (Macklin et al., 1998; Brewer et al., 2000). In this study however, direct digitisation of the river channel planform for the entire trunk channel and major tributary channels was not undertaken. This decision was taken for the following reasons. First, due to the remote settings of channels in the upper reaches of the catchment there were insufficient geo-referencing locations, such as boundary junctions and buildings (the use of which is described in section 3.4.2.3). For aerial photographs in particular, this

Figure 3.11 Weardale study reaches



meant that the accuracy of geo-referencing would be highly variable and inaccurate in the upper catchment as compared to the lower. In many parts of the catchment digitisation would have been unnecessary as many sections of the channel network showed no change between map editions, and more still showed relatively restricted changes to bar extents. Locations where significant changes occurred could be selected for detailed reach scale analysis anyway. Finally the classification of bar area and planform changes allows a more immediate appreciation of channel behaviour. Maps showing the distribution of change allow overall patterns of change to be discerned and displayed with ease. Such an approach offered an extremely efficient way of deriving planform change information at the catchment scale.

Therefore rather than digitise the river channel planform directly from successive maps and/or aerial photographs, sources were compared by means of careful visual comparisons supplemented by measurements of the dimensions of channel change. Firstly the locations of changes in gravel bar area and organisation were mapped onto a base map in the locations at which these occurred. Three categories of change were identified, increase and decrease in gravel area and where the arrangement of the bars had changed, without any change in extent, the section was classified as showing re-organisation of gravel bars. Secondly the styles of channel planform change associated with these changes over the period 1856 and 1991 were classified and mapped. Finally variations in the frequency of gravel bars averaged over the period 1856-1991 were mapped. This approach allows the distribution and type of planform change to be summarised efficiently. The schemes for classifying gravel bar extent and historic channel planform change are discussed further in Chapter 4.

These maps were compiled using the GIS software ArcView and provide a convenient way of presenting the data. The channel change categories were each assigned a colour code and the distribution of each change typology was then digitised on screen using the GIS onto a base map generated from 1:50,000 Ordnance Survey maps of the catchment. The base map was digitised using a Digitisation Table linked to a PC running ArcInfo GIS software. Compiling the results in GIS enabled quantitative measures of the extent and distribution of channel changes to be derived, with relative ease. Specifically this consists of the lengths of channel undergoing change and the locations of these changes with distance downstream. A further advantage of the GIS framework is that it allows the locations

of planform change to be plotted in combination with the distribution of potential controlling mechanisms within the catchment, aiding the analysis.

3.4.2.2 Channel width data

Measurements of active channel widths were made directly from the original archive source, map or aerial photograph every 50 metres along the trunk channel of the catchment (31 km), for the years 1856, 1896, 1951 and 1991. A sampling interval of 50 m provides the highest resolution dataset of channel widths over the historic period for a British gravel-bed river. In order to allow the data to be comparable with the regional mapping outlined above, the active width was subdivided into additional channel components. These were the active and vegetated components of lateral (left or right bank) and medial bars, and the wetted channel width. Measuring the width of active and vegetating gravel bars and the wetted channel enables the dimensions of each component of channel planform to be determined. Vegetating surfaces are measured where they show clear evidence of having formerly been active gravel bars. The former status of a vegetated surface is indicated either by earlier maps or aerial photographs depicting the area as covered by active gravel, or by a visible gravel substrate. Where vegetation cover completely covers the surface of lateral gravel bars resulting in the incorporation of the bar into the floodplain, the bars are no longer a component of the river channel. Analysis of the aerial photographs was hindered locally where the presence of trees along the riverbanks obscured the river channel. Trees tended to be located along the river channel in locations of channel stability, and therefore did not greatly detract from the results (Chapter 5). However, continuous data series are favoured by the statistical techniques (time series analysis) used to examine sequences of data, as such channel width data had to be interpolated over short stretches of channel. Details of the interpolation technique and statistical analysis are discussed in Chapter 5.

3.4.2.3 Reach based planform reconstruction

Reach scale analysis allows detailed comparisons of channel planform to be made for successive surveys. Channel planform detail is digitised from each source, converted to a common scale and reproduced within a single map as a series of channel planform plots. This enables change through time to be presented directly. Different methods for planform comparison have been utilised. Overlaying the sequence of planform plots enables lateral shifts in the channel position to be determined (Hooke, 1987; Lewin and Brindle, 1977; Winterbottom, 2000). However

overlaid channel diagrams can obscure detail where bars are frequent and this can make discerning changes extremely difficult. Alternatively, reproducing planform sequences as a series of independent plots enables the detail of channel changes within the channel itself to be detected (Brewer and Lewin, 1998; Macklin and Lewin, 1989; Passmore et al., 1993), although lateral shifts in channel position are more difficult to detect. Where planform depiction styles varies between map sources it may only be appropriate to plot the centre line of the channel (Warburton et al., 2002). While this precludes the detection of changes within the channel, lateral shifts and changes in gross planform are still shown. A fourth approach is simply to directly reproduce the original maps (Werritty and Leys, 2001) or aerial photographs (Warburton et al., 1993). This reduces the emphasis on the channel and requires copyright permission and as such is only advantageous where planform is complex (braided rivers). In practice meandering channels are often depicted as overlaid planform plots (Hooke, 1995) whereas braided and wandering planforms are depicted as independent plots (Werritty and Ferguson, 1980).

Detailed planform reconstructions nested within the catchment scale assessment, were produced for eight sites in Weardale (Figure 3.2). While the range of data sources available for the catchment wide assessment was restricted to those with total coverage of the study areas, additional sources with limited spatial coverage were also used for planform reconstructions. Examples of this include the use of the railway plans (1844) to extend the range of sources available for Wolsingham and Harperley Park and the use of the tithe plan (1844) at Brotherlee; these provided a valuable insight into channel conditions prior to the Ordnance Survey maps.

GIS software was used for digitising channel planform data from a range of sources, because geo-referencing is an integral component of the digitisation process. Geo-referencing allows differing cartographic sources to be converted to the same scale, allowing direct comparisons between channel planform plots. Geo-referencing requires a number of fixed points located on a plan or map with known co-ordinates. All the maps and plans used to reconstruct channel planform in this study were produced prior to the implementation of the National Grid System by the Ordnance Survey. As such fix points such as field boundaries and wall junctions of buildings had to be located on the historic plan to which an accurate grid-reference could be assigned. In order to determine the National Grid Reference of a specific point (field boundary or wall junction) on a plan it was located on a recent (1970s) 1:10,000 Ordnance Survey map, and its grid reference carefully recorded. This method was

simple to employ, but in practice was difficult to apply to early maps and plans. This was because many field boundaries and buildings were found to have been either removed or relocated. Digitisation requires a minimum of four control points (tic points) evenly distributed across a map. Ideally these tic points should be the same for each cartographic source; in practice, however, this proved to be extremely difficult to accomplish.

All the maps used for the study were geo-referenced using at least of four control points. The process of transforming digitised plots to the National Grid Co-ordinates introduces minor errors, principally related to the difference in accuracy of the early maps which have to be warped to fit the modern National Grid System. In order to minimise these errors as many control points as possible should be used, however in practice locating more than four consistent fixed points proved to be impossible for many sources; particularly in the upper reaches of the catchment where infrastructure is limited. Channel planform data from archive maps was digitised using the digitising table and the software ArcInfo. These plots were then converted into ArcView Shape Files to allow diagrams to be constructed showing the sequential development of channel planform for a given site.

The digitisation of channel planform plots from aerial photographs was carried out using the digitisation software Digger. Aerial photographs were scanned into digital format using a standard flat-bed scanner. These digital images (in TIFF format with a resolution of 600 dpi) were then opened in Digger and geo-referenced using control points as described above. A limitation of using aerial photographs is that they provide a two-dimensional representation of a three-dimensional landscape. Where vertical relief is strong this can lead to a significant spatial distortion. Warping the aerial photograph onto a digital elevation model prior to digitising planform can reduce errors associated with this. However this is a time consuming process and beyond the scope this study. A compromised methodology using as many control points as possible (a minimum of eight) to transform the aerial photographs to National Grid Co-ordinates was employed. Having transformed the aerial photographs to National Grid Co-ordinates the channel detail was digitised on screen. An advantage of using Digger[®] to produce plots of channel planform from each aerial photograph is that it allows the plots to be converted to ArcView[®] Shape Files and incorporated with ease into projects produced using archive maps and plans.

Gravel bars derived from maps and aerial photographs were divided into three classes. Active bars, semi-vegetated bars and vegetated bars. This classification scheme was derived from the mapping style of the Ordnance Survey maps that depict bars composed of bare gravel, and semi vegetated gravel and areas of complete vegetation cover. Bars composed of bare gravel were deemed to be active bars because the lack of vegetation development suggested frequent flow inundation and surface re-working. Vegetation development was taken to be an indicator of bar stabilisation unless evidence suggested it represented recent deposition following a flood i.e. no active gravel was present in the location during an earlier survey. Areas of complete vegetation cover were only mapped where these occurred either within the channel (e.g. medial bars) or were surrounded by active or semi-vegetated gravel.

The GIS software allows supplementary data to be derived with ease, such as gravel bar area, channel sinuosity and number and type of gravel bars to be extracted from each map. The distribution of these 8 detailed study reaches is such that gravel bar area data derived from these reaches can be placed into a regional context compatible with previous investigations by Brewer et al. (2000) and Macklin et al. (1998).

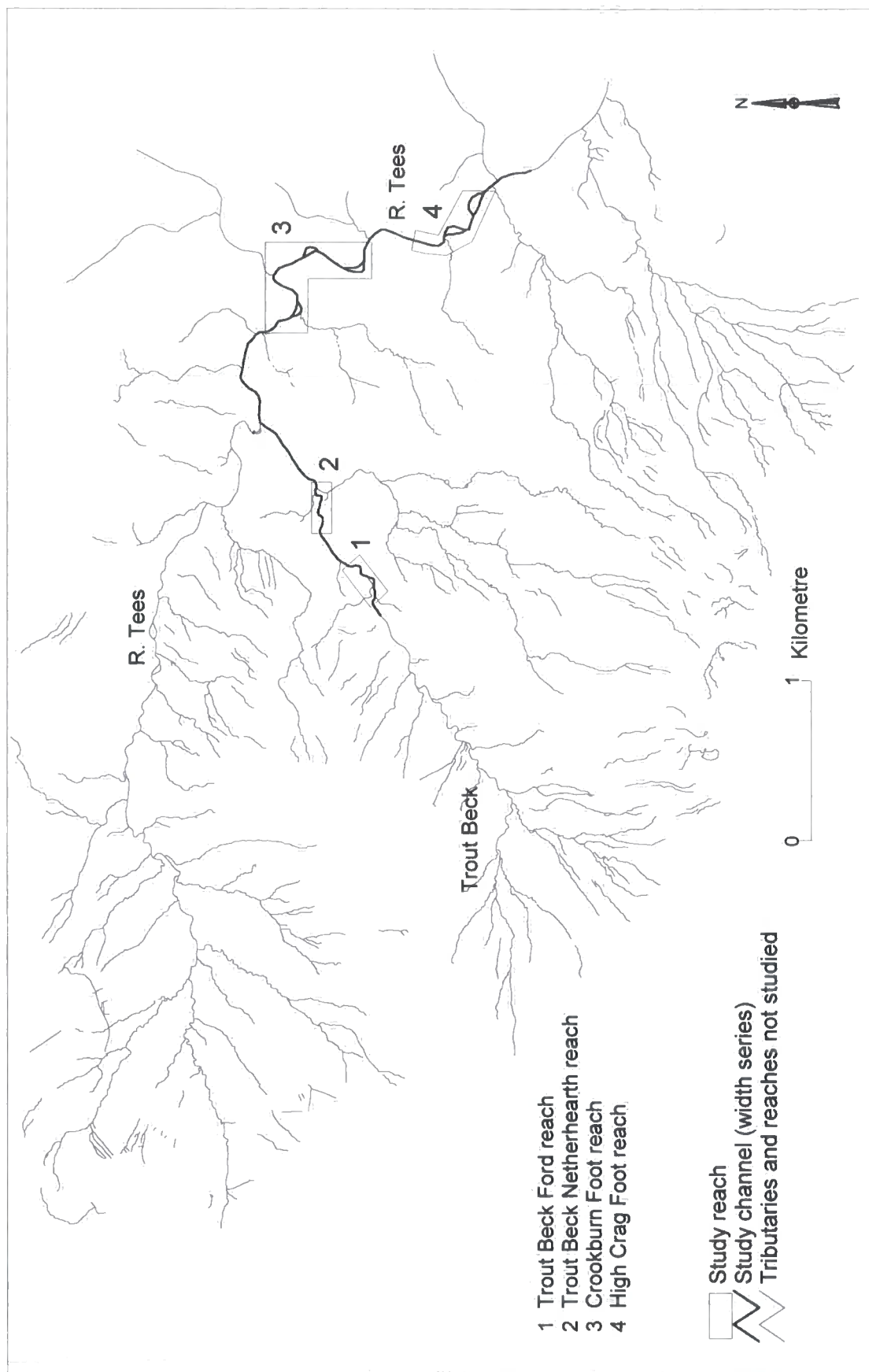
3.4.3. Investigations conducted in upper Teesdale

Investigations conducted in Teesdale consisted of contemporary channel width measurements and channel planform reconstruction, primarily based on historical map and aerial photographs, with additional contemporary mapping of the river channel in key locations following the flood of 30 July 2002 (Figure 3.12).

3.4.3.1 Channel width measurements

The 5.9 km reach selected for analysis extends from the middle reaches of Trout Beck above the Trout Beck Ford reach downstream to the River Tees at Borderon Mere (Figure 3.12). Channel dimensions were recorded at 20 metre intervals along the extended reach. This was designed both to complement the width series analysis conducted in Weardale and increase the spatial resolution of measurements. An increase in the sampling resolution was thought to be appropriate because the Trout Beck channel was of a lower stream order than the River Wear, with a greater variation over a short distance. Additionally, the higher sampling resolution increased the size of the dataset allowing greater confidence in the statistical analysis. The

Figure 3.12 Upper Teesdale study reaches.



statistical tests applied (time series analysis) were the same as those calculated for the River Wear, discussed in Chapter 5.

The comparison of the channel width series between catchments was used to address two key questions:

- Are channel form variations distributed in a predictable manner, for example is there a periodicity of channel width variations?
- To what degree is channel morphology determined by local controls such as bedrock controls and valley gradient?

Measuring channel dimensions with an interval of 20 m over 5.9 km required the development of a methodology that would allow a rapid appraisal to be conducted. This precluded the use of conventional channel survey techniques such as monumented cross-sections, as this is a time consuming process. Therefore the following variables were identified as useful indicators of channel structure and stability that could be identified rapidly in the field:

1. Total channel width measured perpendicularly from bank to bank, or from the margin of total vegetation cover, where bars merge into the surrounding floodplain.
2. The widths of the active and semi-vegetated gravel bars provide a complete representation of channel planform structure.
3. Bank height, to determine if this bore any relationship to channel planform.
4. The channel gradient, to investigate the extent to which channel planform is determined by slope.

3.4.3.2 Reach scale analysis

As in Weardale historical channel planform change was reconstructed along study reaches where significant planform change was found to have occurred over the past 150 years. However in upper Teesdale the method of planform reconstruction differed from that of Weardale. In upper Teesdale fix points from which to geo-reference map and aerial photograph sources were found to be extremely sparse, resulting in insufficient tic points to provide accurate geo-referencing. This precluded the application of GIS techniques for the compilation of sequential channel planform diagrams. Instead, for each of the detailed study reaches, channel planform

reconstructions were produced using the graphics package FreeHand. The channel planform on both the map and aerial photograph sources was digitised on screen. These were then converted to a common scale by overlaying and adjusting the scale of the plot. Well-preserved palaeochannels on the aerial photographs allowed scale adjustment to be achieved with a high degree of accuracy where planform change had occurred. The flexibility offered by FreeHand proved to be advantageous as the Ordnance Survey maps proved to be slightly simplified and it was necessary to use palaeochannels to reconstruct the location of the channel with accuracy. Geomorphological maps produced in the field for each study reach aided this analysis. In the Trout Beck catchment these proved extremely useful for determining the precise impacts of the flood of 30 July 2002, the initial mapping having been completed only two weeks prior to the event. However a significant limitation of FreeHand is that it does not allow bar areas to be derived. While the GIS mapping method would have enabled this, the errors associated with the lack of reliable georeferencing would have been such as to devalue the data. In many cases the errors were likely to have been greater than the changes in gravel bar area.

3.4.3.3 Flood impact investigations

The impact of the 30 July 2002 flood presented a unique opportunity to measure in detail the impact of a large flood event on channel planform. A repeat of the geomorphological mapping exercise was conducted for both the Trout Beck study reaches where the impacts were most pronounced to allow a comparison of pre-flood and post-flood changes to be made and to determine the changes in planform. This then allowed high magnitude flood events to be considered as a cause of historic planform change. A second set of channel widths were also derived for the Trout Beck study reaches, in order to determine how flood events influence channel width series data. Logistical constraints of time and access prevented re-measurement of the entire 5.9 km reach. Significantly a catchment walking exercise conducted in the days after the event to determine the distribution of the flood impacts indicated these two reaches were the most affected in the study area.

3.6 Conclusion

This chapter began by outlining a research framework designed to both complement previous research conducted in upland catchments and to enhance our understanding of river channel behaviour by considering a wide range of potential controlling mechanisms (identified in chapter 2) over a wide spatial scale. The development of a catchment scale approach (implemented for Weardale) allows the connectivity between tributaries and the trunk channel to be evaluated and means questions such as the representativeness of each reach can be avoided. Nested within this analysis, the width series investigations conducted between 1856 and 1991 in Weardale and in 2002 in upper Teesdale enable channel structure to be quantified and compared between these catchments. Furthermore the reach scale reconstructions of historical channel planform change are comparable to those derived from both neighbouring catchments (River Tyne, Macklin, 1997) and other upland areas in the UK.

This chapter also presented a summary of the history of both catchments, extending back into geological time. This reveals that the Wear and Tees catchments shared a very similar geological, geomorphological and environmental history both with each other, and the neighbouring South Tyne. The controls on fluvial processes are very similar for these three catchments, and also to the catchments of the Yorkshire Dales (Howard et al., 1998). The results of this study are therefore comparable to these catchments, but because the geological context and land use histories of these catchments have been determined the results may be compared to other studies in order to enhance our understanding of controls on river channel behaviour at the catchment (Weardale), sub-catchment (upper Teesdale), river (Wear and Tees) and reach scale (Weardale and Teesdale).

Chapter 4 Catchment-scale investigations into historic channel planform change

4.1 Scope of chapter

This chapter outlines the results of the catchment-scale mapping of historic changes in gravel bar extent along the trunk channel and major tributary channels in Weardale (combined length of 103 km). Historical sources enabled changes in gravel bar extent to be determined over four time periods: 1856-1896, 1896-1919, 1919-1951 and 1951-1991. The study focuses on the catchment scale patterns of changing gravel bar extent recorded over these periods. Having determined the nature of changes in sedimentation within the catchment, potential mechanisms that may have caused catchment-scale variations in gravel bar extent are then considered. This chapter focuses on controls operating at or near to the scale of the entire catchment. The significance of recorded changes is assessed by classifying changes in river channel planform coincident with the changes in gravel bar extents. The cause of variations in the magnitude of channel planform activity is then considered.

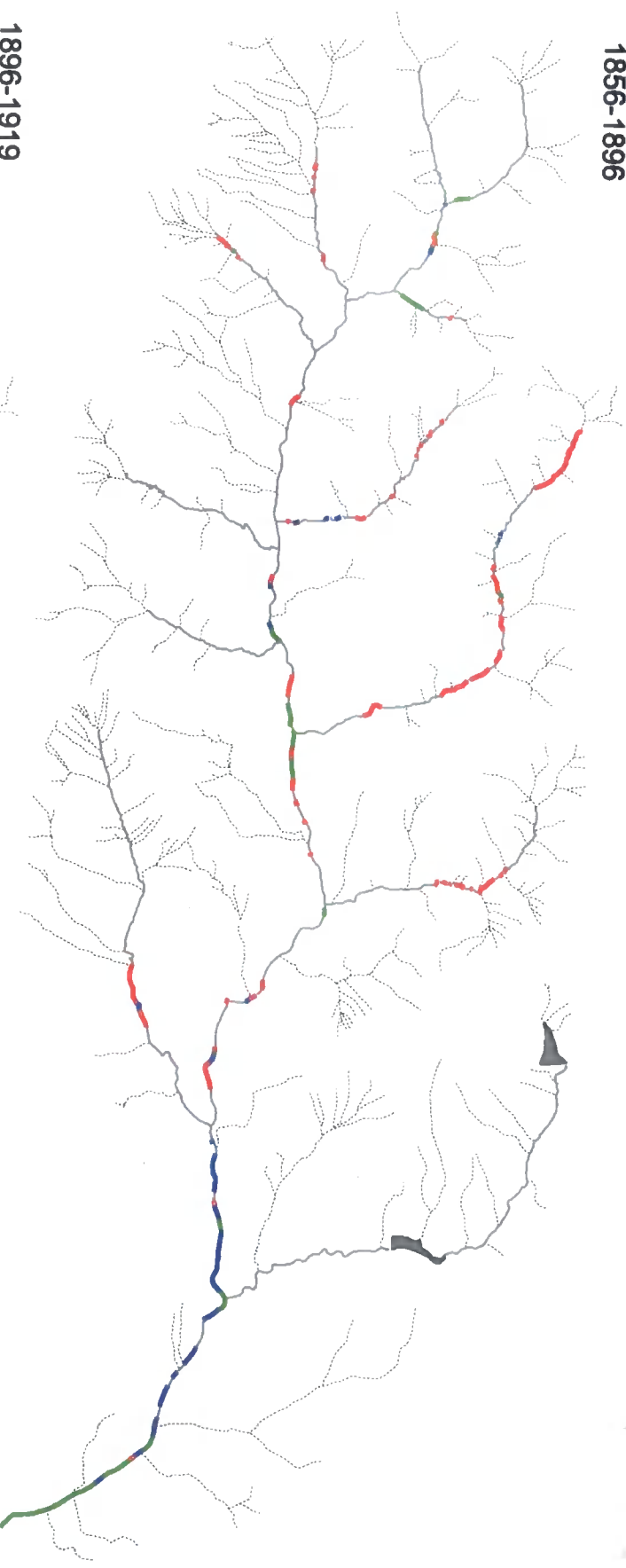
4.2 Catchment-scale appraisal of planform change.

4.2.1 Change in gravel area in Weardale 1856-1991.

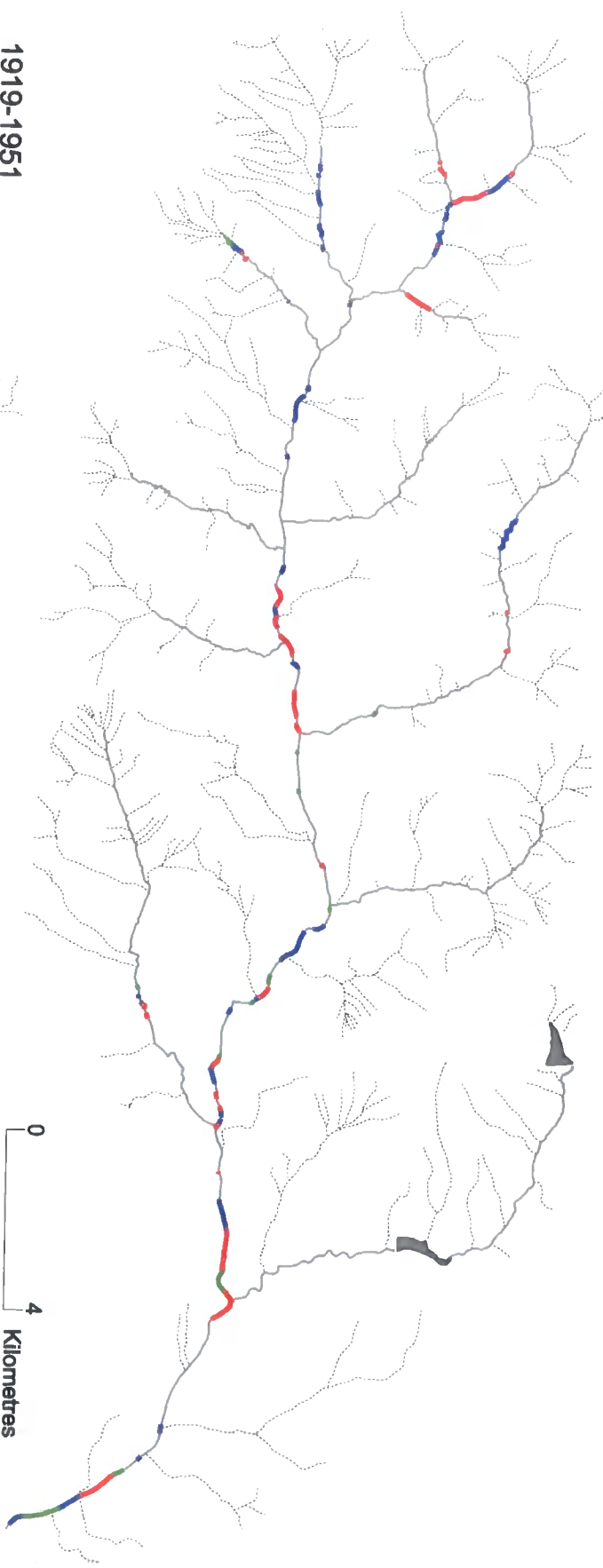
4.2.1.1 1856-1896

The change in gravel bar area between 1856 and 1896 is shown in Figure 4.1a. Decreasing gravel bar area was focused in the upper catchment between 3 and 12 km, while increases in gravel area were concentrated in the lower catchment between 30 and 38km (Figure 4.2a). Declines in gravel were clustered into six tributaries; Burnhope, Ireshope, Middlehope, Rookhope, Stanhope and Bollihope, while the remaining tributaries showed no change in bar extent. Declining gravel area was also the principal form of change in the trunk channel upstream of Frosterley. Overall, decreases in active gravel occurred along 11.5 km of channel as opposed to 7 km, which showed an increase. Reaches showing gravel bar re-organisation with no discernible increase or decrease in gravel area occurred locally throughout the catchment (Figure 4.1a), but were most extensive in the upper middle and lower catchment with a combined length of total of 7.2 km (Figure 4.3a). Reaches showing no change in gravel bars occur throughout the catchment, but are concentrated in the

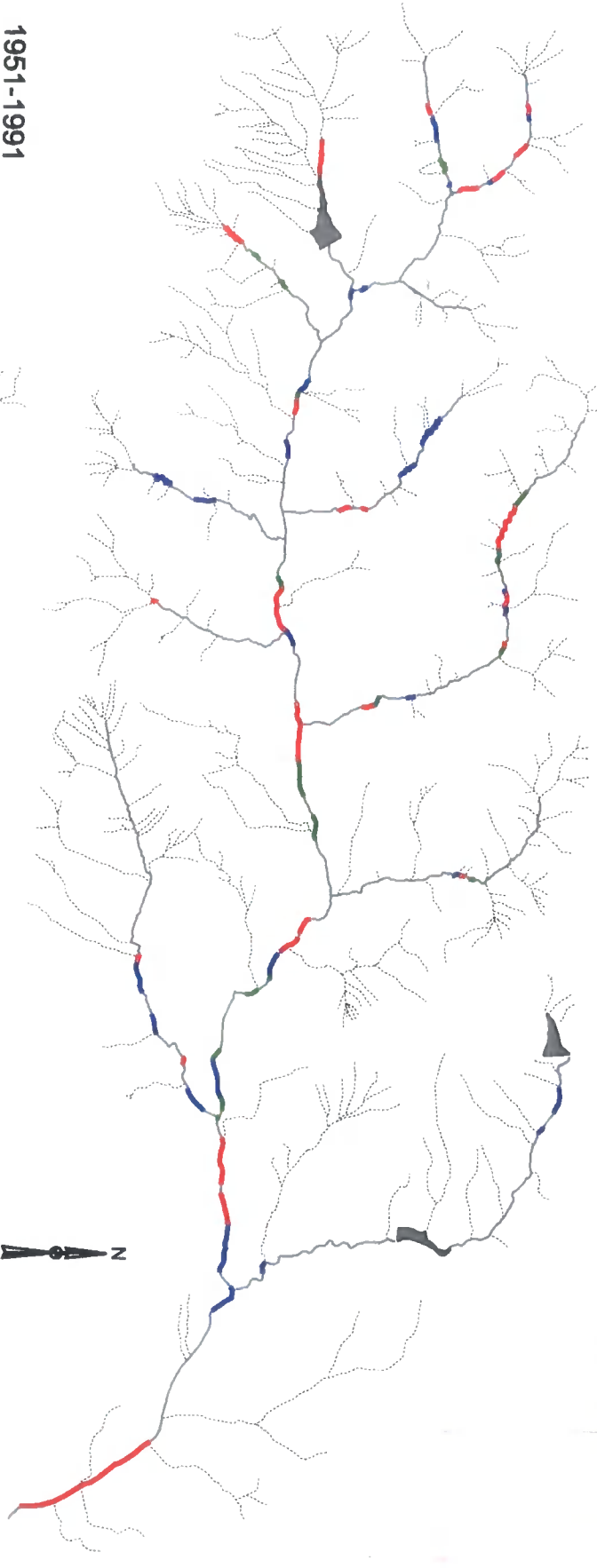
1856-1896



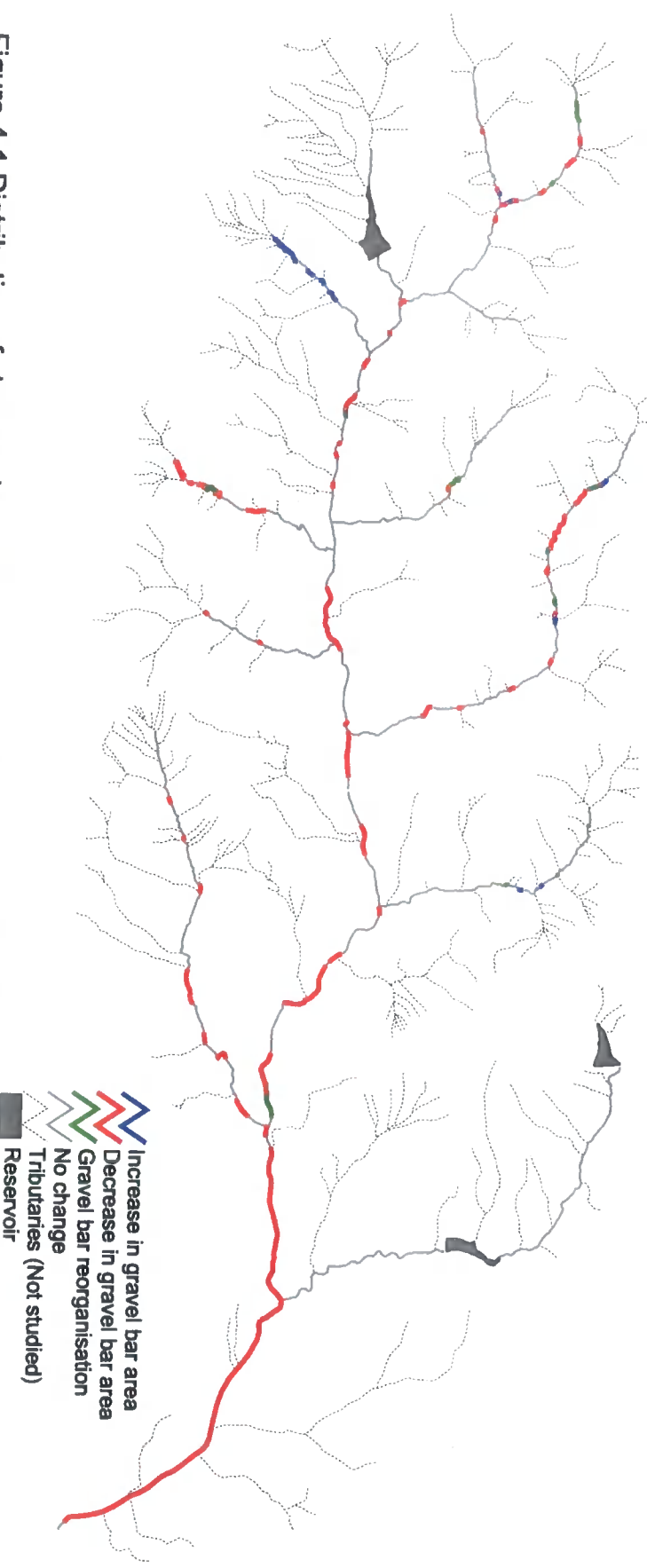
1896-1919



1919-1951



1951-1991



- Increase in gravel bar area
- Decrease in gravel bar area
- Gravel bar reorganisation
- No change
- Tributaries (Not studied)
- Reservoir

Figure 4.1 Distribution of changes in gravel bar area in Weardale 1856-1991.

Figure 4.2 Cumulative change in gravel bar extent for (a) 1856-1896, (b) 1896-1919, (c) 1919-1951 and (d) 1951-1991. The charts combine the lengths of each increase and decrease in gravel area shown on Figure 4.1 by plotting each according to its distance from the source of the specific watercourse.

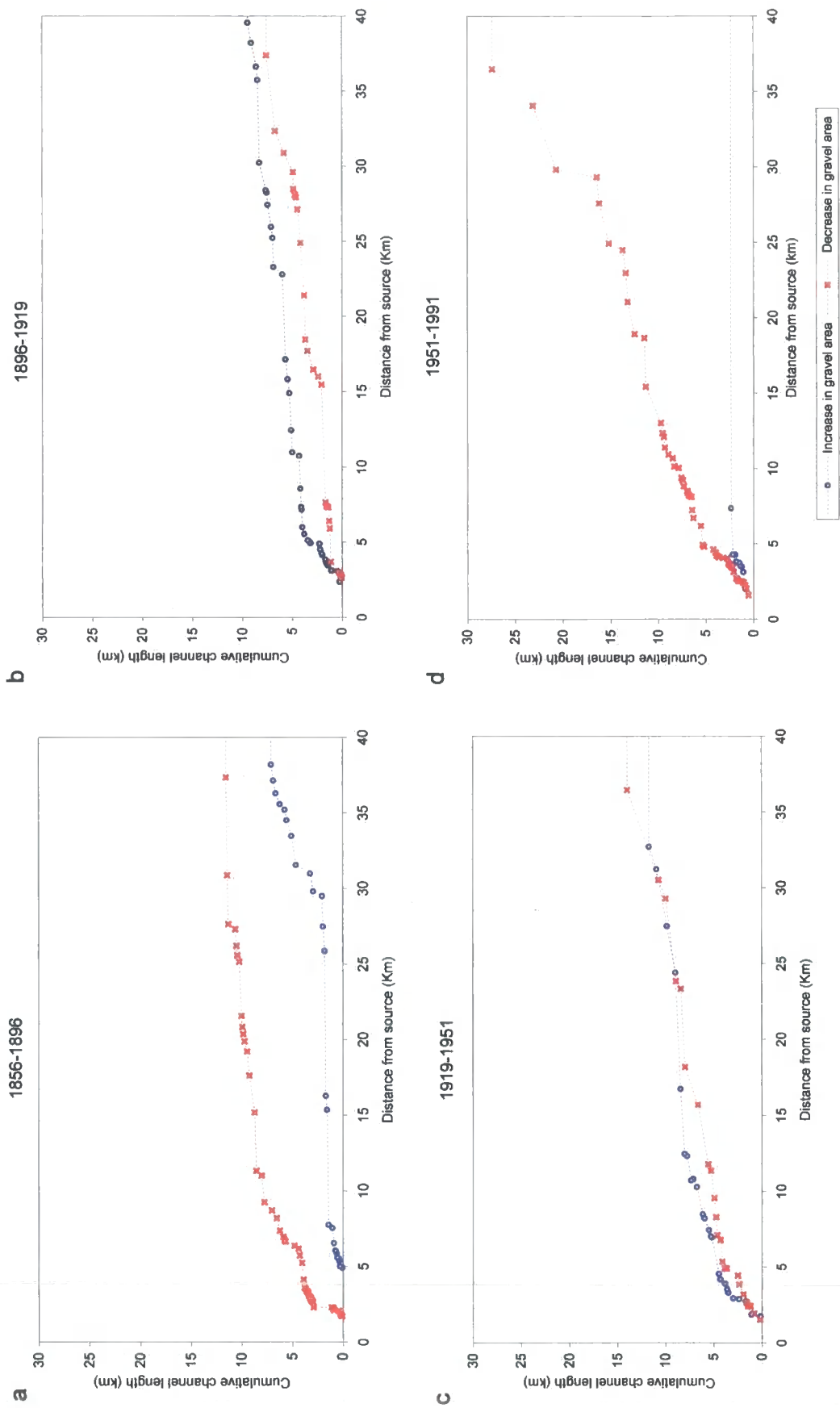
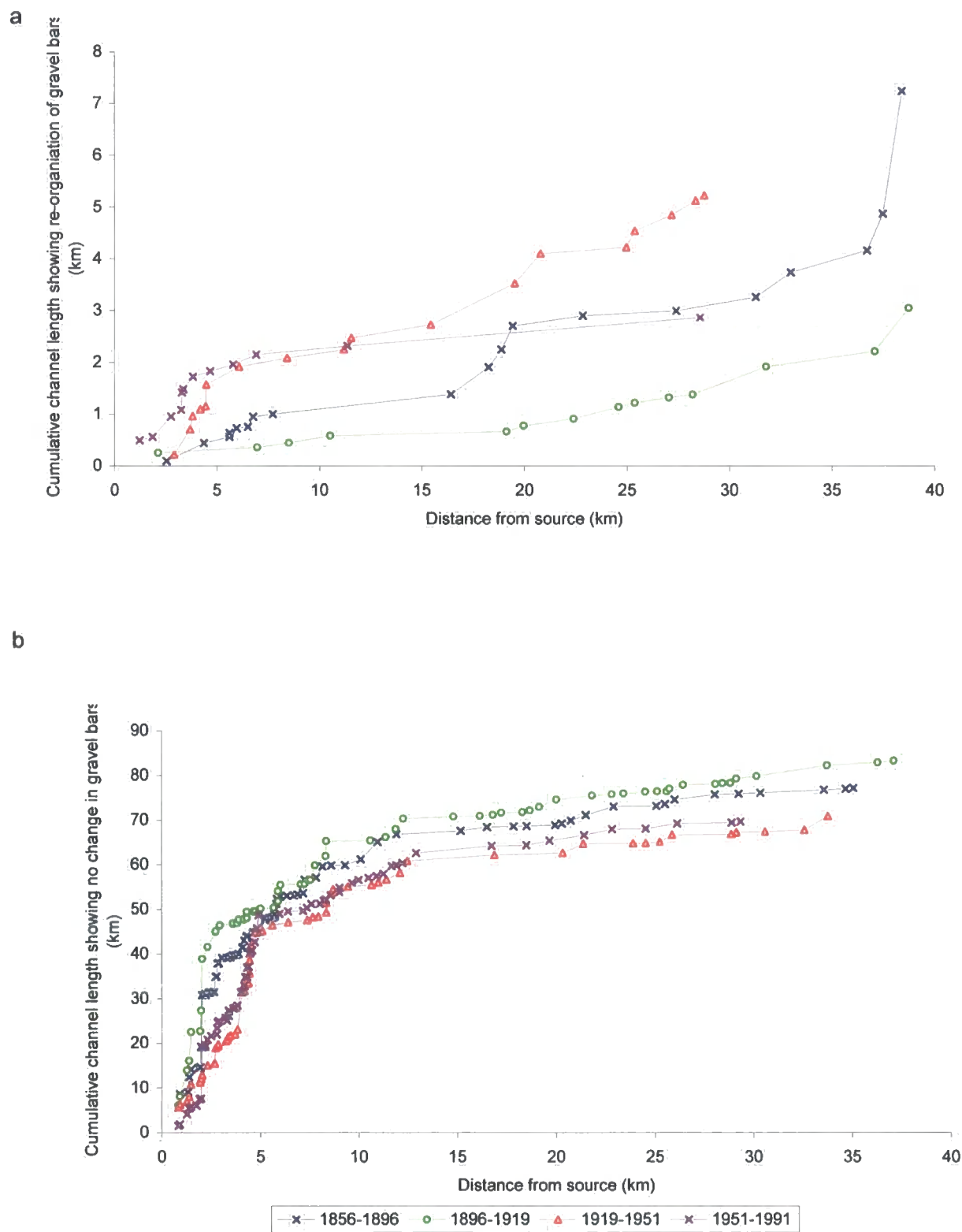


Figure 4.3 Cumulative change in (a) bar re-organisation and (b) no change



upper reaches between 1 and 10 km from source. This clustering in the upper catchment reflects the greater proportion of the channel network in the headwater zone as it encompasses all 12 tributaries studied.

It is important to note that the actual amount of change in gravel area is linked to the size of the channel under consideration. This scale effect is particularly important when changes in gravel area in the tributary channels are compared to the trunk channel or when comparing the upper trunk channel with the lower trunk channel. For example relatively small amounts of gravel are required to cause changes in gravel bar extents over a given length of channel in tributaries as compared to the trunk channel. However in higher order channels there are more numerous sediment sources (including the tributaries). The relatively small quantities of sediment delivered from tributaries combine to induce changes along the trunk channel.

4.2.1.2 1896-1919

Between 1896 and 1919 increases and decreases in gravel area were evenly distributed throughout in the catchment (Figure 4.1b). The focus of channel activity shifted from the northern tributaries to the trunk channel, which showed numerous incidences of gravel area change. Several tributary streams showed no change: Middlehope Burn, Stanhope Burn, Waskerley Beck, Swinhope Burn and Westernhope Burn. While both increases and decreases in gravel area have a relatively uniform distribution, in detail there are some important differences (Figure 4.1b). Increasing gravel area is more significant than decreasing gravel area in the upper catchment. Between 5 km and 10 km increases in gravel area are three times more extensive than decreases in gravel area (Figure 4.2b). In the mid-catchment however, decreasing gravel area is significant between 15 and 19 km (Figure 4.2b) mainly in four relatively long reaches experiencing a decrease (Figure 4.1b). The increasing gravel area significant around 23 km (Figure 4.2b) is related principally to a long reach (900 m) showing an increase (Figure 4.1b). Decreasing gravel area is slightly more significant than increasing gravel area around Wolsingham (Figure 4.1b) at 30 km (Figures 4.2b). In the lowermost reaches of the catchment, reaches showing an increase in gravel area are more extensive than decreases (Figure 4.2b).

Increases in gravel area were slightly more extensive than decreasing gravel area, with total lengths of 9.4 km and 7.6 km respectively (Figure 4.2b.). This was mainly due to a decline in the length of channel showing a decrease in gravel bars.

Reaches showing an increase in gravel bar extents became more extensive in the upper and middle catchment. There was a significant decline in the length of channel showing re-organisation of gravel bars, with such reaches being distributed relatively evenly (Figure 4.3a). Many reaches formerly showing bar re-organisation remained active but experienced a decline in gravel bar extent. The amount of channel showing no change in gravel bars increased since 1856-1896, reaching its maximum historical extent (Figure 4.3b).

4.2.1.3 1919-1951

Changes in gravel bar area were fairly evenly distributed throughout the catchment during the period 1919-1951 (Figure 4.1c). Many of the reaches showing change during this period were also active during 1896-1919 (Figure 4.1b) however the extent of gravel changes increased, with all the tributary streams examined showing some change (Figure 4.1c). Increases in gravel area were slightly more extensive than decreases in the upper catchment between 2 and 13km (Figure 4.2c). In the mid-catchment, between 15 km and 18 km, decreases in gravel area were more extensive than increases in gravel area, indicating a net decrease in gravel area in the middle catchment (Figure 4.2c). In the lower reaches, between 25 and 34 km both increases and decreases in gravel area were of similar extent. However in the lowest section of the catchment decreasing gravel area dominates (Figures 4.2c), reflecting a decline in gravel area along a 3 km section of channel (Figure 4.1c). In total, decreasing gravel area was more extensive than increasing gravel area at 12 km and 14 km respectively. The significance of reaches showing a re-organisation in gravel bar increased since the period 1896-1919, and were distributed throughout the upper and middle portion of the catchment, but were absent in the lower reaches (Figure 4.3a). The length of channel showing no change declined throughout the catchment and in the upper and middle catchment this represented an historic low (Figure 4.3b).

4.2.1.4 1951-1991

While many of the reaches showing changes in gravel bar area over this period were also active during previous time periods, the extent of changes within the catchment increased dramatically (Figures 4.1d and 4.2d). The channel network was dominated by decreasing gravel bar area (Figure 4.1d). Increases in gravel area were confined to the upper catchment close to the source (Figure 4.2d) such as in the lowest reaches of Killhope and Wellhope Burns, and the upper and middle Ireshope Burn

(Figure 4.1d). The cumulative length of channel showing a decrease in gravel area rises relatively uniformly down catchment (Figure 4.2d). The majority of decreases in gravel area in the upper catchment were restricted to numerous short reaches whereas changes clustered into fewer but longer reaches in the lower catchment (Figure 4.1d). The trunk channel was dominated by decreasing gravel bar areas. Despite a slight increase in the significance of reaches showing bar re-organisation in the upper catchment, this declined in the middle catchment and represented a pronounced reduction in extent since 1919-1951 (Figure 4.3a). In the upper and middle reaches of the catchment the length of channel showing no change increased slightly (Figure 4.3b), but was now at its lowest total extent due to an increase in channel activity in the lower reaches of the catchment during this period (Figure 4.1c and d).

4.2.2 Summary of changes in gravel area in Weardale 1856-1991

Throughout the study period (1856-1991) the channels within the catchment have shown a complex pattern of changes in gravel bar extent and the locations of change showing considerable variation (Figure 4.1 and 4.2). The total extents of each change typology for each time period are summarised in Table 4.1. The actual proportion of the channel network showing a change in gravel bars is relatively small, ranging from 17% (1896-1919) to 32 % (1951-1991). The most striking result is the large proportion of the channel network showing a decrease in gravel bar area between 1951 and 1991, 27% of the channel network.

Despite only representing around a quarter of the channel network, the results show a number of important general patterns. Between 1856 and 1896 the tributaries show a broadly synchronous pattern of decreasing gravel and some bar re-organisation, leading to a dominance of decreasing gravel bar area in the upper catchment during this period (Figure 4.2). Similarly the upper trunk channel also showed a dominance of decreasing gravel area during this period. However, the lower reaches of the trunk channel were dominated by increases in gravel area (Figure 4.1). Over the period 1896-1919 activity within the tributary channels declined and variations in the trend in gravel area changes developed. The trunk channel also switched to a more complex pattern of change as distributions of increasing and decreasing gravel bar areas became more uniform in the catchment (Figure 4.2). This local variation in the direction of gravel bar changes along the tributaries and trunk channel continued over the period 1919-1951 (Figure 4.2). In contrast to the opposing behaviour of the

upper and lower catchment during the period 1856-1896, the period 1896-1951 showed no particular clusters of sections experiencing increasing or decreasing bar extents at the catchment-scale. The period 1951-1991 was defined by a catchment wide decline in the extent of gravel bars within the channel network. There were a few local variations, the most significant being Ireshope Burn, which was characterised by an increase in the extent of gravel bars.

Table 4.1 Total length of channel (km) showing change in gravel bars between 1856 and 1991. Figures in brackets indicate percentage of total study channel length (km).

Change in bar area	1856-1896	1896-1919	1919-1951	1951-1991
Increase	7 (7%)	9.4 (9%)	12 (12%)	2.5 (2%)
Decrease	11.5 (11%)	7.6 (7%)	14 (13%)	27.4 (27%)
Re-organisation	7.2 (7%)	3 (3%)	5 (5%)	2.9 (3%)
No change	77.3 (75%)	83 (81%)	72 (70%)	70.2 (68%)

Significantly the majority of the channel network showed no change in the extents of gravel bars during each time period. Reaches with no changes in gravel bar extent generally correspond to locations where the channel structure is controlled by bedrock. Bedrock control can be total, where the channel is formed entirely into bedrock, or partial where only the bed is composed of bedrock. Such confinement prevents lateral channel adjustment and concentrates flow at high stage, increasing the shear stress experienced at the bed ensuring efficient sediment transfer rates. Bedrock beds prevent significant accumulations of sediment because the friction between sediment within the channel and the bed is limited, reducing resistance to shear stress. Bar size is limited by the short residence time of sediment in the channel, as reaches where bedrock control occurs act as transfer reaches. Additionally, local sediment supply can also be low where resistant strata such as limestone and dolerite confine the channel, this is common in the lower reaches of the tributaries.

In Weardale much of the upper reaches of the channel network are subject to bedrock control where, despite frequent gravel bars, no changes in bar extent have occurred. Examples include upper Westernhope Burn, upper Bollihope Burn and upper Wellhope Burn. The lower reaches of the tributaries are also subject to

bedrock control as they typically descend through bedrock gorges. Bedrock control also occurs locally along the trunk channel. The importance of bedrock control is confirmed by the fact that reaches where changes in bar extents occur tend to be concentrated in the same locations during differing time periods. Significant sedimentation and therefore channel change is concentrated in where the influence of bedrock is low. The majority of the sediment stored within the study channels in Weardale is concentrated into approximately 30 % of the channel network, where confinement is limited.

4.2.3 Determining the significance of change in bar areas on channel planform

Changes in channel planform in gravel-bed rivers occur primarily through changes in the size and arrangement of gravel bars (Figure 1.1). While the changes in gravel bar extent and organisation show some interesting spatial and temporal patterns over the historic period, the actual magnitude of these changes varies according to both channel size (scale effect) and the degree of channel confinement. In addition to bedrock dominated reaches, lateral confinement is also provided by unconsolidated sediments such as till, solifluction deposits along valley sides and river terraces. These deposits are more susceptible to erosion than bedrock and tend not to confine the channel to the same degree as bedrock. They also act as additional sources of sediment.

In order to determine the significance of the changes in gravel bars (Figure 4.1) the types of channel planform changes have been summarised into categories. These are based on the form of channel change that produced the greatest lateral change along a given length of channel over the historic period. That is, the dominant form of channel change over the last 150 years is recorded. For example bend changes may also be associated with localised bar re-working, however the movement of the bend tends to be the dominant response of the channel. Four styles of dominant channel planform change could be identified:

1. Channel planform remained stable but gravel bar extents varied (limited lateral change).
2. Changes in bend amplitude occurred in sinuous (meandering) reaches (changes in channel position in the order of one to two wetted channel widths).

3. Gravel bar re-organisation involving localised re-routing of channel thalweg in reaches with low channel sinuosity (change in wetted channel position in the order of one to two wetted channel widths).
4. Extensive and persistent channel changes involving the re-working of mid-channel bars (changes in wetted channel width greater than two channel widths).

The distributions of these changes in channel planform are shown in Figure 4.4. The timing and trend of activity within reaches classified into these categories may be determined by comparing Figure 4.4 with Figure 4.1; the key findings are summarised below. The magnitude of channel planform change corresponds broadly to the distribution of gravel bars within the catchment (Figure 4.5) as defined in Figure 4.6. Variations in the extent of gravel bars reflect the degree to which the channel acts as a sediment store, which is related to the degree of lateral confinement and gradient of the channel. In reaches of high confinement and/or channel gradient, sediment transport dominates. Here bar frequency is determined by sediment supply. Frequent bars can occur but tend to be restricted to sites of high sediment supply, such as the upper reaches of the tributaries, while lower in the catchment such bars occur infrequently. Where confinement and/or gradient are low, storage dominates and gravel bars are numerous or extensive (Figure 4.6). Particularly extensive bars occur where the channel is inset within easily eroded materials such as low alluvial terraces the channel responds through bank erosion. Bank erosion contributes further sediment to the river channel enhancing the channel changes. This sequence of events explains the development of reaches with extensive and persistent channel changes involving the re-working of gravel bars. Similarly wide reaches such as these will also be more susceptible to declines in sediment supply leading to a reduction in the extent of gravel bars. Such reaches represent sedimentation zones. The variation in the extent of gravel bars, while divided here into a fourfold classification scheme, lie on a continuum reflecting the degree to which reaches operate as transfer reaches or storage reaches (Figure 4.6).



Figure 4.4. Map showing the distribution of channel planform change typologies in Weardale over the period 1856-1991.

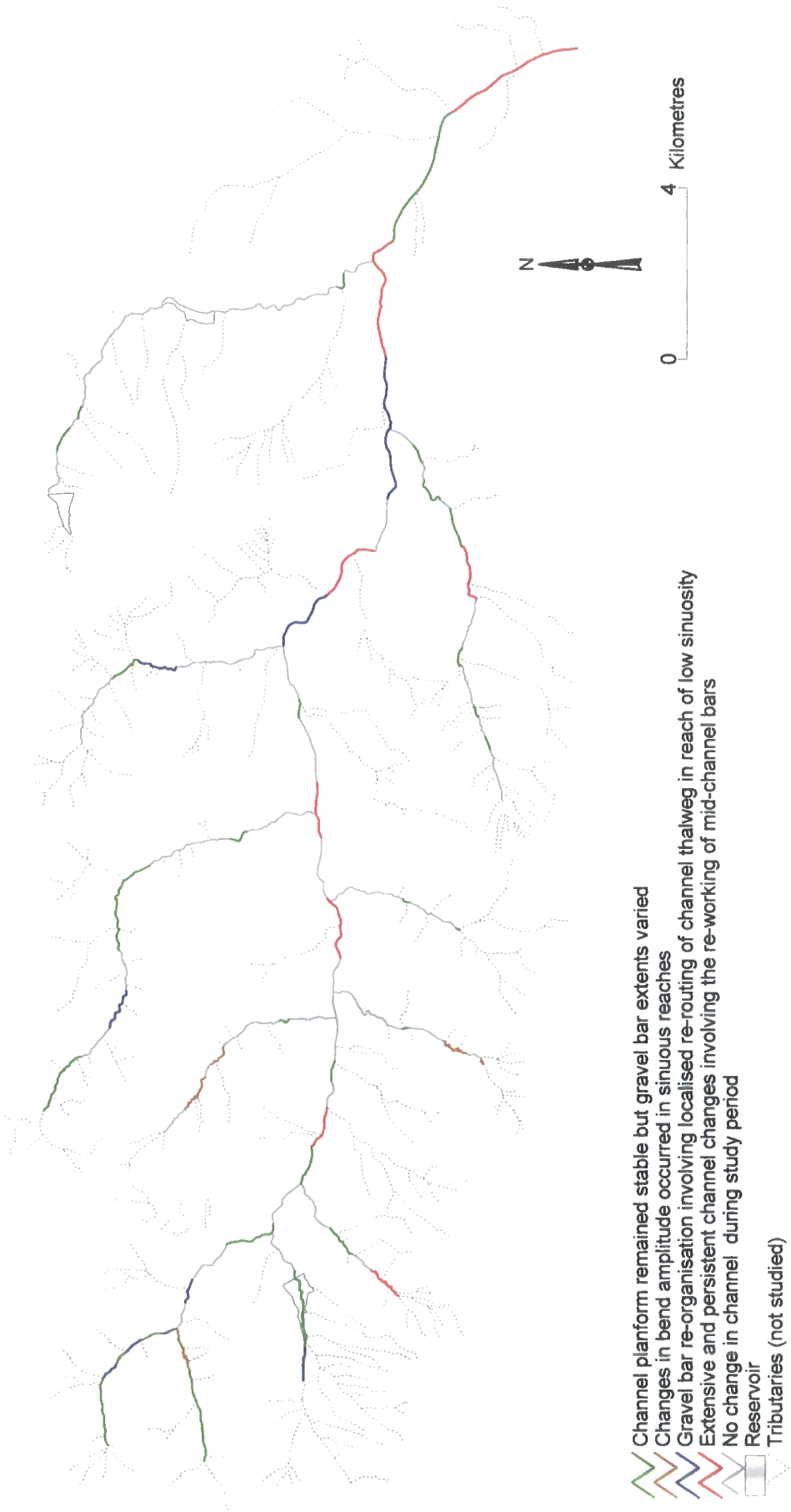


Figure 4.5. Generalised distribution of the frequency of gravel bars in Weardale over the historic period.

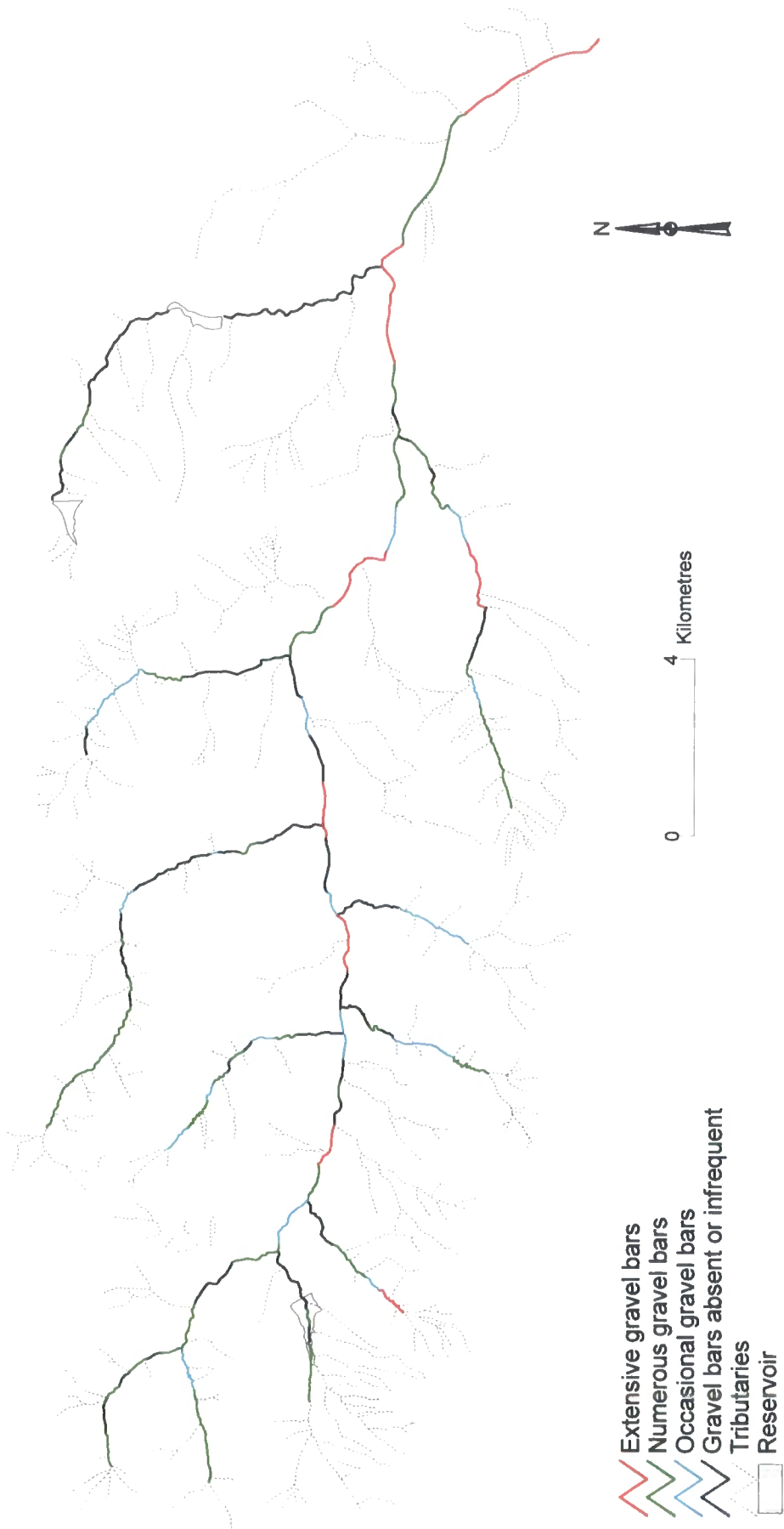
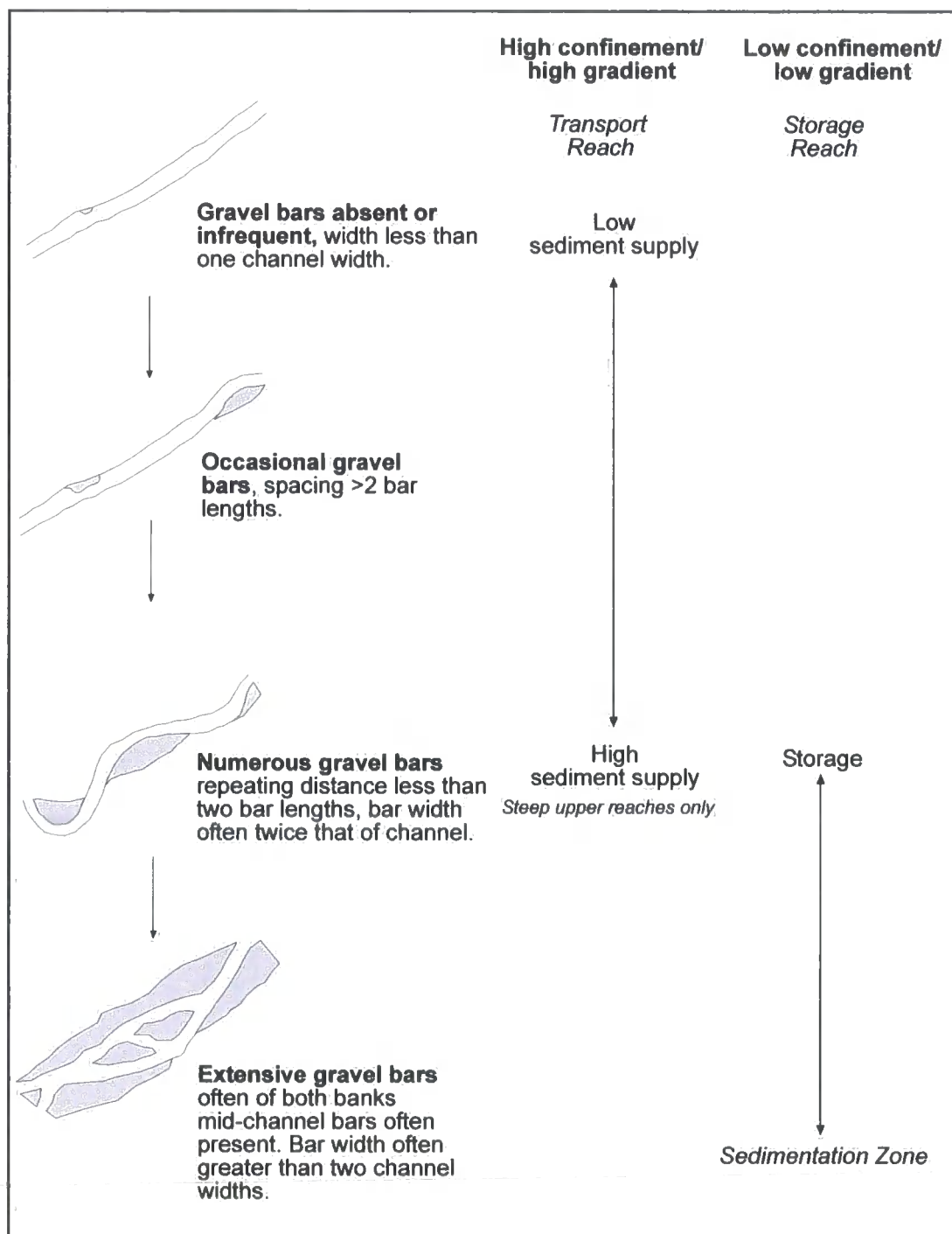


Figure 4.6 Classification scheme summarising the variation in the extent of gravel bars observed along the Weardale study channels. The range of bar frequencies illustrates the relative importance of sediment transfer and storage, which is governed by the degree of channel confinement and gradient. Note that sediment supply rates are relative.



4.3 A preliminary assessment of the cause of observed changes in the gravel bar extents within the catchment

4.3.1 Controls on gravel bar extent

The extent of gravel-bars is controlled by the balance between vegetation growth, bank erosion rates, sediment supply and sediment transport rates (Brewer et al., 2000). Vegetation colonisation of gravel bar surfaces is a particularly important cause of the decline in gravel bar extent (Brewer et al., 2000). The degree of vegetation colonisation is determined by the rate of sediment deposition and the frequency of bar surface re-working, both of which are determined by flood magnitude and frequency. Sediment is delivered to the channel by bank erosion, rates of which are influenced both by flood magnitude and frequency and also sedimentation within the channel as this can promote lateral erosion. As such, gravel bar extent is principally determined by the balance between sediment supply and discharge and is reflected in the scheme developed by Schumm (1977) summarised in Table 1.1. Gravel bars act as sites of sediment storage. In gravel-bed channels these are particularly important components of the sediment transfer process, as coarse sediment (bed load) only moves short distances during competent flows. Sediment transfer in gravel-bed rivers is a discontinuous process, involving a continual exchange between mobile and stored material (Church et al., 2001). As such the transfer of coarse sediment through a reach can be summarised in the form of a sediment budget:

$$V_o = V_i - \Delta V \quad (4.1)$$

(Ham and Church, 2000, p 1124)

where V_o is sediment output and V_i is sediment input. The change in bar area represents change in sediment storage (ΔV) and is the net difference between erosion of a bar, vegetation colonisation of the bar surface (incorporation into the floodplain) and bar growth via deposition. As coarse sediment transfer involves constant exchanges between mobile and stored sediment, change in gravel bar area provides an indication of the changing quantity of sediment moving through the channel network. An increase in sediment supply will increase deposition and lead to bar enlargement, where lateral confinement permits. Conversely a decrease in sediment supply will lead to a reduction in bar extent due to both erosion of the bar and a decline in deposition on the bar surface which allows vegetation colonisation.

Sediment budgets, such as that described above, require information concerning the volume of sediment within gravel bars (Ham and Church, 2000). This study however only considers changes in the area of gravel bars. Nevertheless field observations indicate that in North Pennine rivers, gravel bar area provides a useful indication of changing sedimentation patterns. Changes in the lateral extent of bars tend to vary closely with change in volume of sedimentation (Figure 4.7). Increases in gravel bar extent occur via lateral spreads of gravel deposited during large floods or through lateral accretion on the margins of the channel (Figure 4.7b). Both these mechanisms lead to a change in the area of active gravel, even where sediment volumes are small. Decreases in bar extent (Figure 4.7c) tend to be dominated by vegetation colonisation of bar surfaces as described by Brewer et al., (2000). Although erosion of bar margins also leads to a decline in bar area, this appears to be less important. These styles of changes reflect the relatively wide and shallow structure of gravel-bed channels where lateral confinement is low (Figure 4.7).

Mapping the change in gravel bar area through time provides a technique for rapidly appraising long-term changes in the sediment balance of reaches within the catchment. This chapter therefore provides an indication of long-term (150 years) catchment-scale (103 km of channel) variations in the supply and transfer of sediment through the catchment.

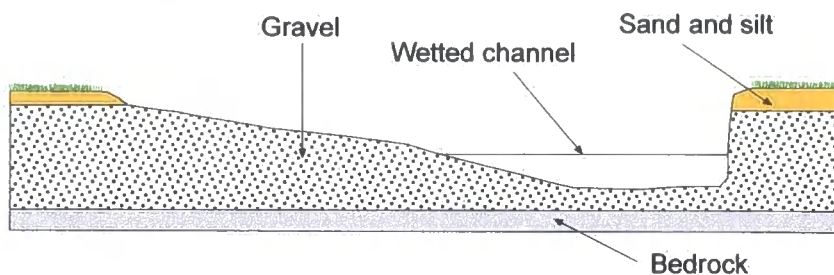
4.3.2 Implications for catchment sediment balance in Weardale

The changes in gravel bar area (Figure 4.1) reflect changes in the overall sediment balance of the catchment. Between 1856 and 1896 the tributaries and upper trunk channel showed a decline in gravel extent (a sediment deficit), whereas the lower reaches of the trunk channel showed an increase in gravel area (a sediment excess). It appears therefore that sediment was being transferred from the upper catchment to the lower catchment during this period. However over the period 1896 to 1951 catchment-scale transfers of sediment ceased and localised variations in sediment balance dominated. In the period 1951-1991 however, a catchment wide decline in the extent of gravel bars occurred. This suggests catchment scale processes began to dominate channel planform change once more.

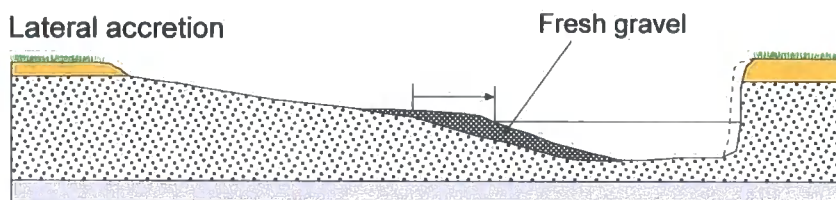
These catchment-scale sedimentation patterns can be investigated more rigorously through a quantitative analysis of the sequences of increasing and decreasing bar extents. Transition frequency matrices provide a means of quantifying the number of

Figure 4.7 Cartoons illustrating mechanisms of increasing and decreasing bar area, showing: (a) initial condition, (b) increasing bar area and (c) decreasing bar area.

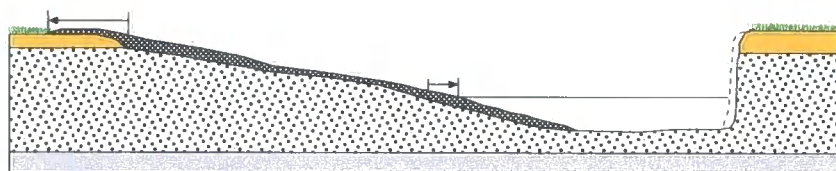
a Initial condition



b Increase in bar area

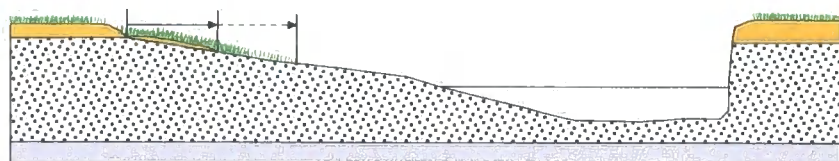


Over-bank spread

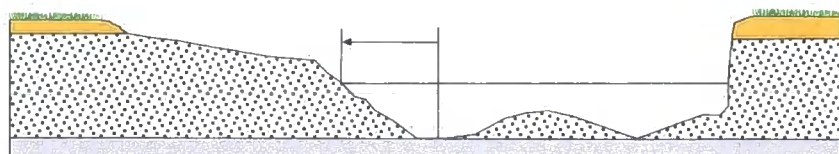


c Decrease in bar area

Vegetation colonisation



Bar erosion



different types of transitions along a data sequence (channel). In this case, transitions from an increase or decrease to the next increase or decrease downstream have been summed (Table 4.2). This can be used to determine whether changes in the extent of a bar are determined by changes in the bars upstream. For example, it can be used to test whether an increase in bar area occurs downstream of a bar showing a decline in extent, suggesting sediment movement downstream. Since the analysis is concerned with the patterns of changing bar extent, sites where no changes in bar extent have occurred are excluded from the analysis because these represent locations where changes in bar extent are prevented by lateral confinement. Such reaches represent transfer reaches where sediment is conveyed efficiently with minimal impact on channel morphology.

Transition frequency matrices are generally used to examine linear sequences of data, however the results of the catchment scale analysis lie within a dendritic channel network, which complicates the analysis. The network was therefore divided into three components: the tributaries, the trunk channel and confluences (Table 4.2), each of which was analysed separately. The tributaries and the trunk channel represent linear data sequences. At the confluences of tributaries and the trunk channel however the situation is more complex, as changes below the confluence may be dictated either by the trunk channel or the tributary channel upstream (this is not a linear data sequence). At confluences the lowest change on the tributary was compared to the next change downstream along the trunk channel. As the trunk channel represents a higher order channel than the tributaries (there is an abrupt transition in channel scale), changes along the trunk channel are more likely to reflect changes further up the trunk channel. Transitions across confluences are therefore likely to be of secondary importance to sequences of events down either the tributaries or the trunk channel.

The transition frequency matrices reinforce the catchment-scale patterns described above. Between 1856 and 1896 the tributaries and confluences behaved uniformly, being dominated by decreases in gravel extent following decreases upstream. The trunk channel at this time exhibited a more complex pattern, indicating it was not behaving as uniformly as the tributaries. This reflects a transitional zone of both increases and decreases in gravel area in the middle reaches of the trunk channel between the decrease-dominated upper trunk channel and the increase-dominated lower trunk channel (Figure 4.1a). Transition types were more varied throughout the catchment during the time periods 1896-1919 and 1919-1951 with no clear

Table 4.2 Transition frequency matrices showing the number of transitions from increasing or decreasing gravel area to increasing or decreasing gravel area, for each time interval.

	Tributaries				Trunk channel				Confluences (lowest change on tributary to next change on trunk channel)			
	Downstream (to)		Upstream (from)		Downstream (to)		Upstream (from)		Downstream (to)		Upstream (from)	
	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease
1856-1896												
Upstream (from)	Increase	3	4	7	Increase	9	Increase	5	Increase	0	Increase	1
	Decrease	4	25	29	Decrease	5	Decrease	9	Decrease	1	Decrease	5
		Total		36		Total		14		Total		6
												7
1896-1919												
Upstream (from)	Increase	8	5	13	Increase	9	Increase	10	Increase	3	Increase	1
	Decrease	5	5	10	Decrease	8	Decrease	6	Decrease	0	Decrease	2
		Total		23		Total		14		Total		2
												6
1919-1951												
Upstream (from)	Increase	8	10	18	Increase	3	Increase	4	Increase	1	Increase	2
	Decrease	7	2	9	Decrease	5	Decrease	3	Decrease	3	Decrease	0
		Total		27		Total		7		Total		3
								8				3
								15				6
1951-1991												
Upstream (from)	Increase	4	3	7	Increase	0	Increase	0	Increase	0	Increase	0
	Decrease	5	23	28	Decrease	0	Decrease	16	Decrease	2	Decrease	6
		Total		35		Total		16		Total		8
												8

dominance of a particular change typology. Significantly, the transition frequency matrices do not provide clear evidence of local sediment transfers, which should be characterised by a increase in bar area downstream from a decrease in bar area. Rather there are sequences of increases and sequences of decreases in addition to transitions from increase to decrease and vice versa. This reflects the relatively long time intervals being considered; the period 1856-1896 is 40 years, 1896-1919 is 23 years, 1919-1951 is 32 years and 1951-1991 is 42 years. Over these time periods sediment can move over relatively long distances, producing sequences of declines or increases. Local transfers are relatively difficult to detect due to the relatively long time intervals. The period 1951-1991, however, was clearly dominated by sequences of declining gravel bar extents reflecting the synchronous channel behaviour in the catchment at this time.

The results are further supported by the calculation of fixed probability vectors based on the transition frequencies (Table 4.3). Fixed probability vectors indicate the likelihood of an increases or decrease in gravel area following a given change (either increase or decrease). These are calculated for each time interval. Derived from the transition frequency matrices, these are calculated by dividing the row total of the frequency matrix by the total number of transitions in the matrix (Table 4.2). The results reveal the dominance of decreasing gravel extents in the tributaries during 1856-1896 (a decrease has an 81% chance of following a given change), and throughout the catchment between 1951 and 1991 (a decrease has an 80% and 100% chance of following a given change) (Table 4.3). They also reveal that the period between 1896 and 1951 was characterised by a more even chance of increases or decreases following a given change.

In summary therefore the increases and decreases in gravel bar area mapped throughout Weardale provide an indication of the sediment balance of differing parts of the catchment over the period 1856 to 1991. The periods 1856-1896 and 1951-1991 showed systematic changes in sedimentation patterns within the catchment. This suggests that during the mid-late nineteenth century a pulse of sedimentation migrated down the catchment. Following a period of more localised channel behaviour during the early twentieth century a catchment-wide decline in active gravel occurred. Potential causes of these changes in channel behaviour are now considered.

Table 4.3 Fixed probability vectors showing the likelihood of either increasing or decreasing gravel area occurring downstream of an increase or decrease for each time period, in differing parts of the catchment.

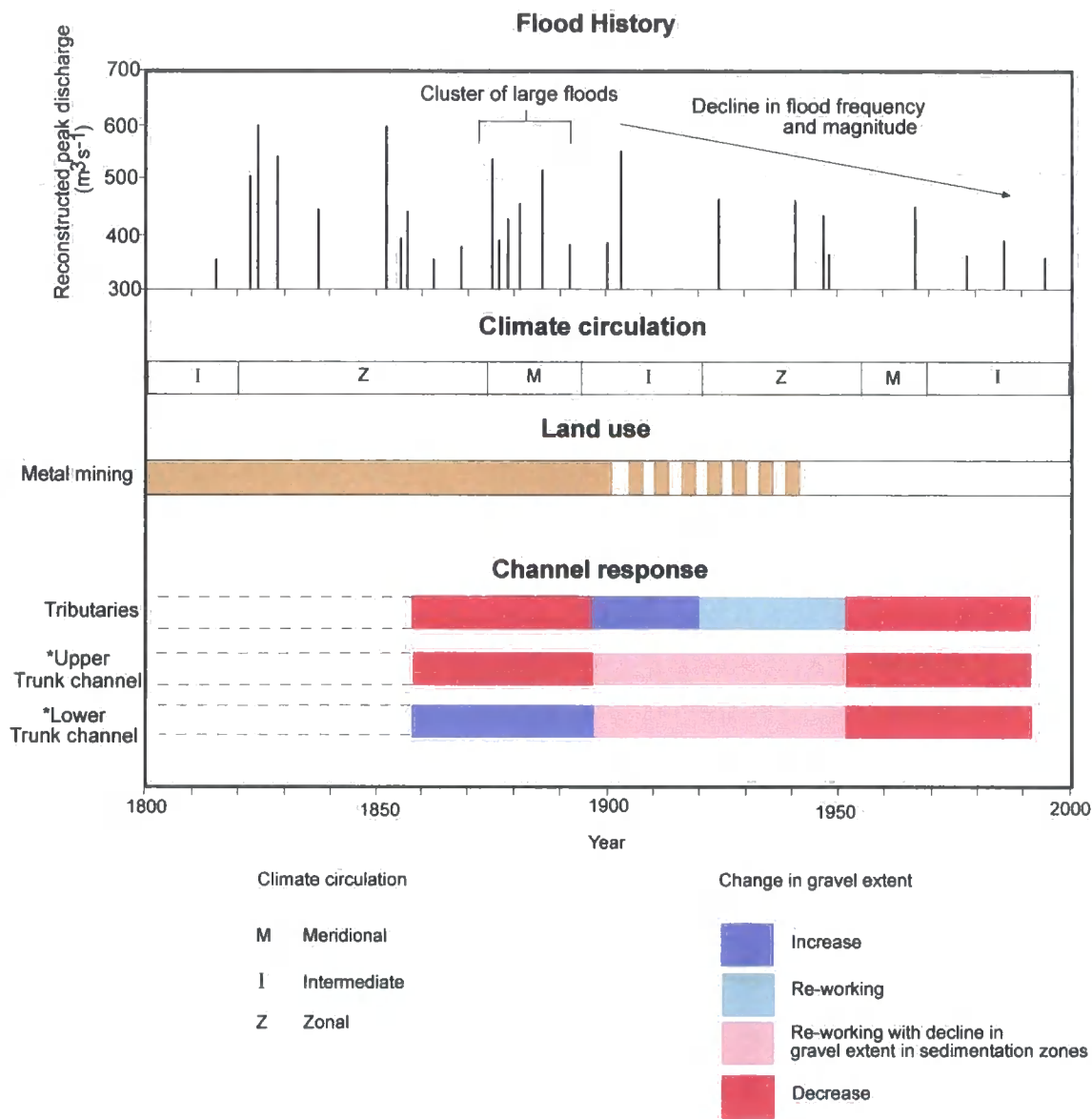
	Tributaries		Trunk channel		Confluences (lowest change on tributary to next change on trunk channel)	
1856-1896	Increase Decrease	19% 81%	Increase Decrease	50% 50%	Increase Decrease	14% 86%
1896-1919	Increase Decrease	57% 43%	Increase Decrease	58% 42%	Increase Decrease	67% 33%
1919-1951	Increase Decrease	67% 33%	Increase Decrease	47% 53%	Increase Decrease	50% 50%
1951-1991	Increase Decrease	20% 80%	Increase Decrease	0% 100%	Increase Decrease	0% 100%

4.3.3 An initial appraisal of mechanisms influencing catchment-scale sedimentation patterns

Several factors were identified in Chapter 2 that are known to influence the channel planform of upland gravel-bed rivers. The systematic behaviour of the river channels over the periods 1856 - 1896 and 1951 - 1991 suggests influences were occurring at the scale of the entire catchment. At the catchment scale, climate and land use combine to dictate river channel behaviour. The relationship between changes in gravel bar extent in Weardale, climate circulation, flooding, and metal mining in Weardale is illustrated in Figure 4.8. Climatic variations affect the behaviour of entire catchments through changes to flood frequency and magnitudes. In terms of land use only metal mining operations were sufficiently extensive in Weardale during the historic period to have initiated a catchment wide channel response. The interaction of flood frequency and magnitude, and catchment-scale land use must therefore be considered.

Sedimentation in the lower reaches of the catchment between 1856 and 1896 coincided with a phase of meridional circulation associated with frequent high magnitude flood events. Research conducted in the Tyne catchment indicates the large floods associated with meridional climate circulation caused channel incision throughout the Tyne catchment (Rumsby and Macklin, 1994; Passmore and Macklin, 2000, Newson, 2003). However, in Weardale it appears that a pulse of sedimentation migrated from the tributary channels, showing a decline in gravel bars, to the lower reaches of the catchment where sedimentation was occurring. The transfer of sediment from the tributary channels may have been initiated by the large floods associated with meridional climate circulation of the period (Figure 4.8). The decline in gravel bar extent in the tributary streams occurred during the main phase of metal mining. It appears therefore that sediment input from mines was insufficient to maintain large bar areas as the floods of the late nineteenth century transferred sediment downstream very effectively. Significantly, increases in gravel area appear to have occurred in some reaches of the South Tyne catchment during this period (Macklin and Lewin, 1989; Passmore et al., 1993; Macklin, 1997). These local increases in gravel-area have been linked to metal mining. These increases in gravel bar extent tended to be clustered in the upper trunk channel (for example The Islands in the South Tyne, Macklin and Lewin, 1989) whereas in Weardale it appears sediment was transferred further downstream.

Figure 4.8 Summary diagram comparing catchment flood history (Law et al., 1998), general climate circulation, and metal mining with resulting channel response* .
 * The trunk channel is divided into upper and lower above and below Stanhope respectively.

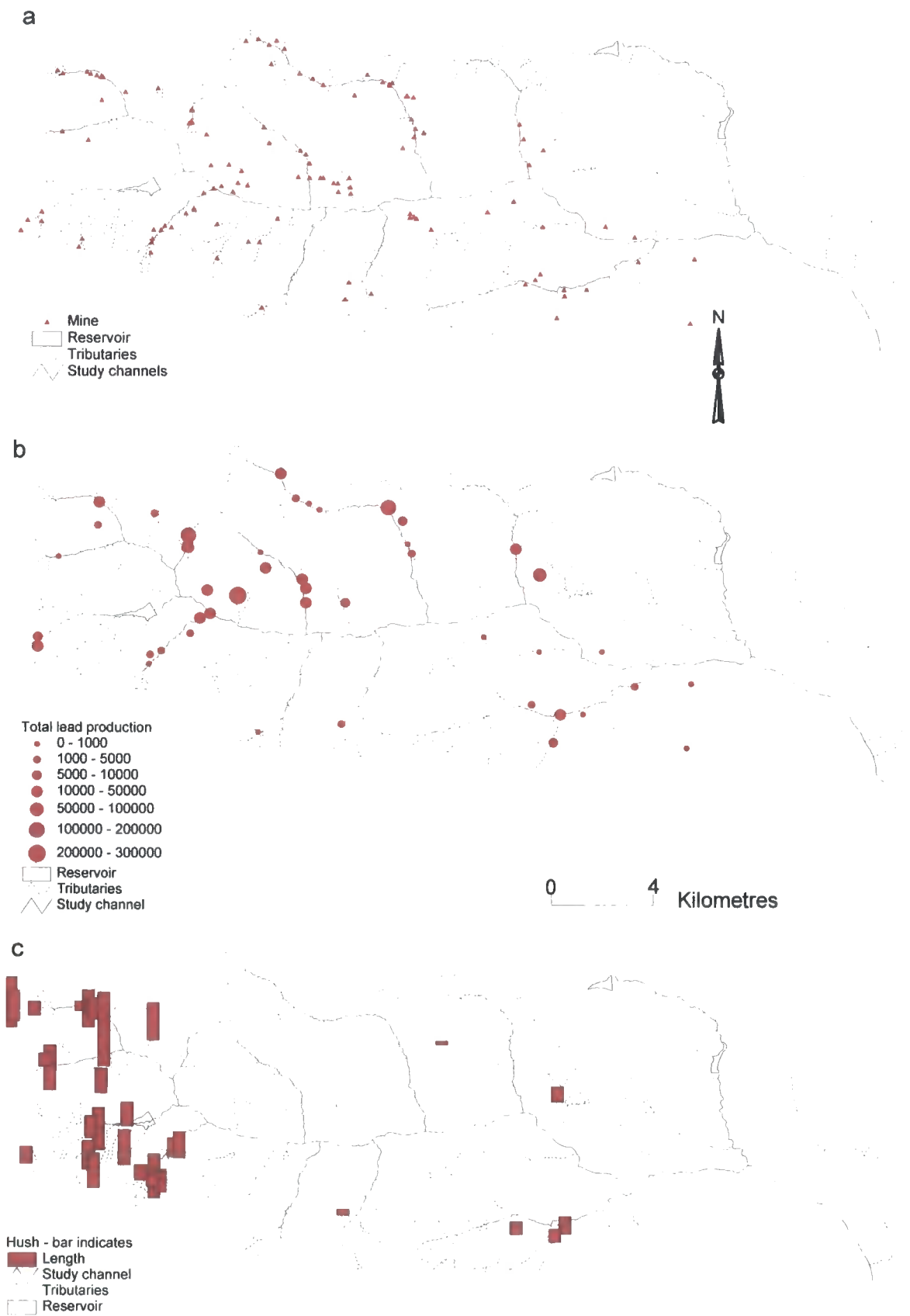


Metal mining was particularly significant in Weardale throughout the nineteenth century, and was widespread in the catchment (Figure 4.9). The sedimentation in the lower reaches of the catchment between 1856 and 1896 may have been enhanced by sediment delivered to the channel, as was the case in the Tyne catchment (Passmore et al., 1993). The release of fine heavy metal contaminated sediment has been reported widely in mined catchments (Passmore and Macklin, 1994). This sediment retards vegetation growth (Lewin et al., 1983) and may have enhanced the impact of floods through destabilisation of the riverbanks in the reach and prevented bar stabilisation between floods.

Following this down-catchment migration of sedimentation a phase of renewed deposition occurred in the tributary channels (Figure 4.8). This increase in gravel bar extent at a time of low flood frequency and magnitude may also have been promoted by metal mining. The lack of large floods at this time prevented this material from being transferred to the trunk channel. Those tributaries that showed an increase at this time were located downstream of metal mines (Figure 4.1 and 4.9). The phase of reworking between 1896 and 1951 corresponded with low flood frequency (Figure 4.8) resulting in only localised patterns of increasing and decreasing gravel extent. A reduction in vegetation colonisation of bar surfaces due to the presence of phytotoxic fine sediment will have promoted the reworking of gravel bars during the intermediate phase as vegetation stabilisation of the bars was prevented. The reductions in gravel bar area between 1951 and 1991 represent the main channel response to declining sediment loads. This occurred as a result of the cessation of metal mining and declining flood frequency and magnitude. However, it took 50 years following the end of widespread mining for significant vegetation colonisation of gravel bars to occur in the catchment, due to the presence of heavy metals.

While the River Wear flood record for the nineteenth century generally corresponds to climate circulation, this is not the case for the twentieth century (Figure 4.8). The zonal climate phase between 1920 and 1954 was characterised by few large floods as compared to the zonal phase during the nineteenth century. Perhaps more significant is the lack of large floods during the meridional phase between 1955 and 1969 (Figure 4.8). In the Tyne catchment a series of large floods occurred at this time and resulted in bed incision throughout the Tyne catchment (Newson, 2003). In Weardale, however, large flood events were found to be associated with sedimentation. The lack of sedimentation in Weardale during the twentieth century

Figure 4.9 Location of (a) metal mines in Weardale, (b) total known production and (c) hush location and relative size (based on data from Hutton and Warburton, unpublished). For tributary names see Figure 3.9.



and synchrony of channel behaviour reflects the lack of floods recorded in the historic flood record (Figure 4.8). However, as discussed above, sedimentation during the nineteenth century was also encouraged by catchment land use. The relationship between flood frequency and magnitude and channel behaviour is explored in chapter 8.

4.4. Summary

1856 - 1896

The catchment experienced a decrease in the extent of gravel bars in the tributaries, upper and middle trunk channel, and an increase in the lower reaches of the trunk channel. This appears to have been initiated by a change in the climate circulation pattern, complemented by sediment supply from metal mining within the catchment. This generated a pulse of sediment within the catchment, which was clearly expressed in the lower reaches of the trunk channel by widespread increase in gravel bar extents.

1896 - 1919

Despite a relatively low flood frequency and magnitude this period was characterised by deposition in several tributary channels and a phase of re-working along the trunk channel. Sedimentation in these tributary streams is likely to have been generated by metal mining operations within the catchment, both as a result of the direct input of coarse sediment and through channel destabilisation through phytotoxic fine sediment deposition. Heavy metal contamination also appears to have promoted the phase of re-working along the trunk channel; indeed, the sections of the channel network that show this pattern of reworking are located in areas where metal mines were most productive (Figure 4.9).

1919 - 1951

The reworking phase continued within the catchment and increased to cover a greater proportion of the channel network (Figure 4.2). This increase in re-working within the catchment resulted from the combination of a change to zonal climate circulation (and as a result an increase in frequency of moderate flood events) and the presence of heavy metal contamination within the stream channels.

1951 - 1991

This period was marked by a catchment-wide decline in the extent of gravel bars as a result of a decline in both flood frequency and magnitude. Importantly the River Wear flood history in Weardale questions the significance of the meridional climate circulation between 1953 and 1969. The absence of a significant increase in flood frequency and magnitude at this time explains the lack of sedimentation in the trunk channel. Declines in gravel bar extents were produced by vegetation colonisation resulting from a decline in the frequency of bar inundation, and were not caused by erosion of the gravel bars, even in the tributary channels.

4.5 Conclusions

1. While flood frequency appears to be the primary controlling mechanism, its influence is modified by the influence of metal mining and catchment geomorphology.
2. The behaviour of channels is dependent on the interaction of climate, land use and the geomorphological setting, particularly confinement. This means that the nature of channel behaviour can be extremely site specific. This appears to have been the case between 1896 and 1951.
3. During periods of high flood frequency and magnitude such as 1856-1896 local influences within tributary catchments may be over shadowed and the tributaries behave in a synchronous manner. Such behaviour in Weardale appears to have generated a pulse of sedimentation in the catchment. Similar synchronous behaviour can occur during declines in flood frequency such as between 1951 and 1991.

While these catchment scale investigations have enabled a good appreciation of the behaviour of the channels in the catchment during the last 150 years, there are a number of issues which require further clarification. This chapter examined the pattern of changes in gravel bar area and its impact on channel planform. However, in order to appreciate the variation in both the extent of gravel bars and magnitude of channel changes, these must be quantified. Chapter 5 quantifies channel changes along the length of the trunk channel; this offers the potential to identify sediment transfers, particularly those associated with the re-working phase between 1896 and 1951. While catchment-scale processes such as climate are clearly important, a range of additional, typically localised, influences are known to impact channel

planform. The extent to which such local influences may combine to produce channel behaviour recorded at the catchment scale requires evaluation. In order to gain a better understanding of the causes of sedimentation patterns and planform change, planform change is reconstructed from a range of sites in the catchment in Chapter 6. Detail available from cartographic sources reveals additional information about channel changes prior to 1856. The importance of flood frequency and magnitude is evaluated in chapter 8 with reference to the findings in Teesdale detailed in chapter 7.

Chapter 5 Channel width series

5.1. Scope of chapter

This chapter examines variations in channel width along the trunk channel of the River Wear from 1856-1991. Measurements of channel width were derived at 50 metre intervals for the years 1856, 1896, 1951 and 1991 enabling changes over the periods 1856-1896, 1896-1951 and 1951-1991 to be determined. Having examined the changes in channel planform over each time interval in detail, variations in the total channel width of the river channel during each year were analysed using time series analysis. Total channel width encompasses the combined width of the wetted channel together with active and vegetating bars, and as such summarises channel planform for each series. Time series analysis was used to summarise the channel planform structure at each date to assess changes through time and determine any regularities in width variations (periodicity).

5.2. Change in channel width between survey years.

5.2.1. 1856-1896

The river channel in 1856 was dominated by discrete zones of wide active gravel bars, separated by reaches with smaller bars (Figure 5.1). There are locations where no gravel bars occur, in particular the first 6.75 km of channel representing locations of bedrock control and decline in frequency downstream. The presence of these gravel bars results in a marked variation in the total width of the river channel (Figure 5.2a). Sites of particularly extensive gravel bars (Figure 5.2b) correspond to the sedimentation zones identified in chapter 4 (Figure 4.4). Reaches are classified as sedimentation zones on the basis of extensive active gravel bars (>3 channel widths), present in more than one time interval, together with evidence of bar organisation. The discrete nature of these sedimentation zones and their proximity to tributary confluences (Figure 4.4) suggest a significant component of the sedimentation in these reaches may be derived from the tributaries. However when the locations of these confluences are plotted these tend to occur downstream from

Figure 5.1 Channel width structure of the River Wear in 1856.

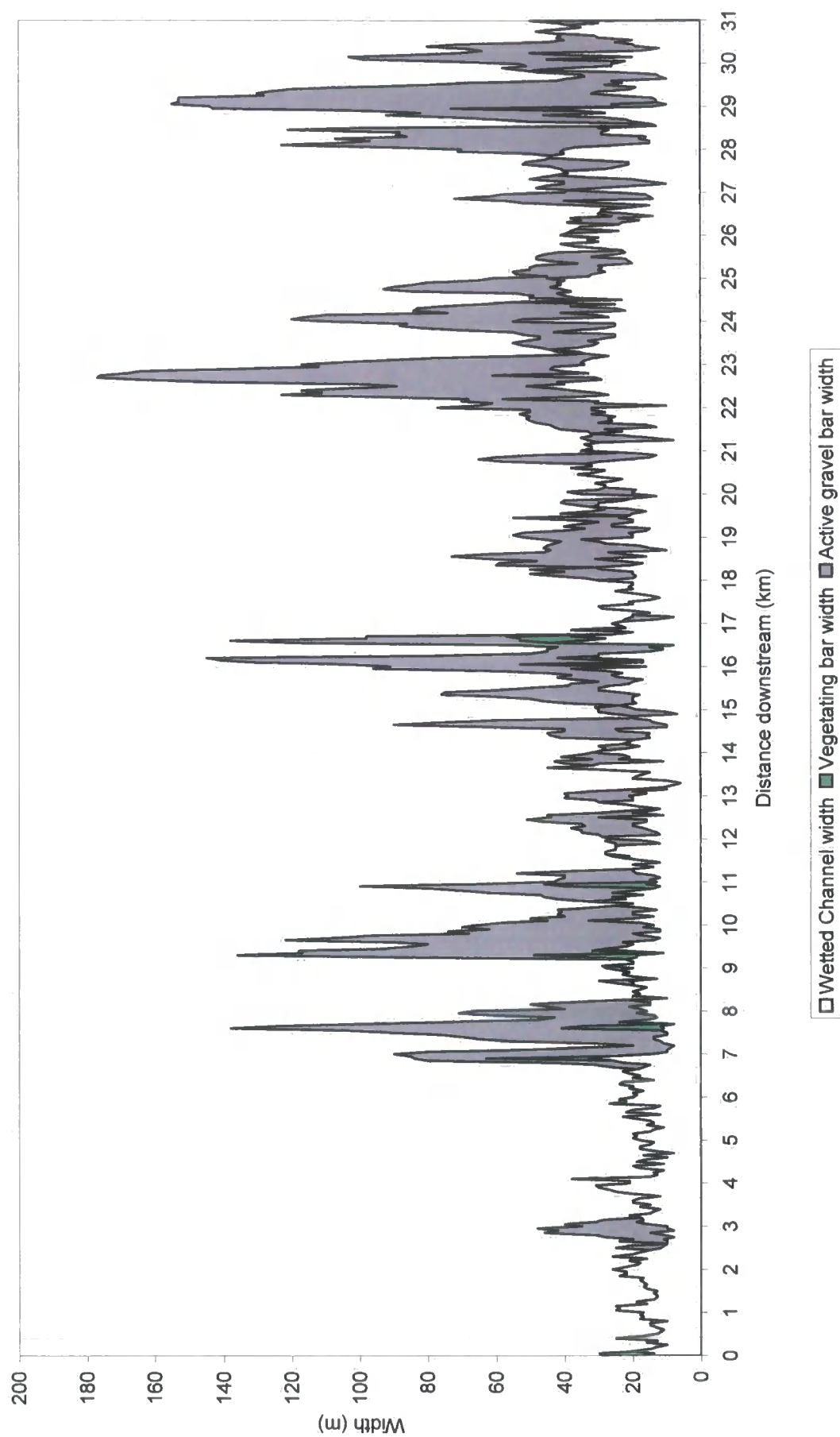
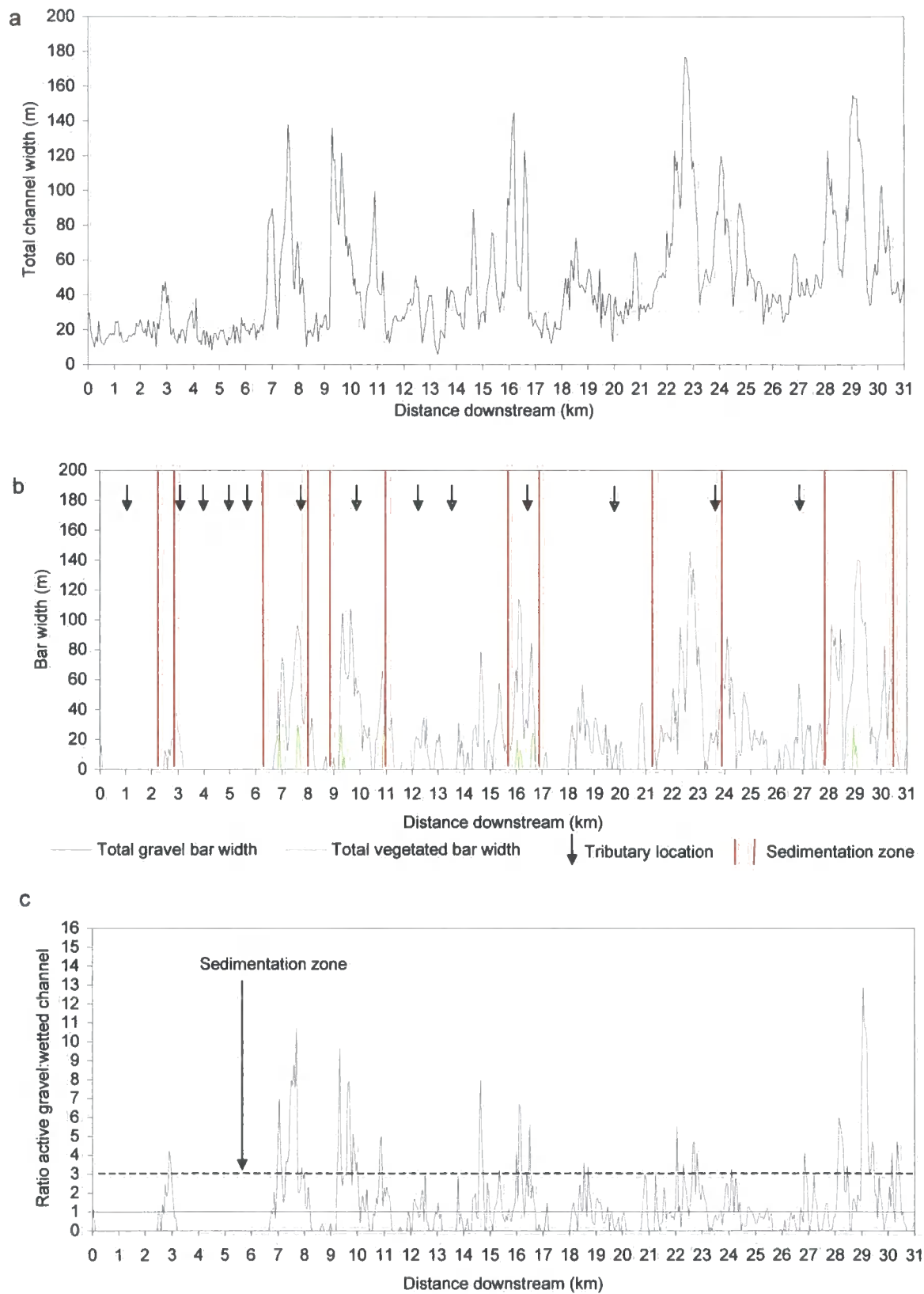


Figure 5.2 Channel structure during 1856, (a) total channel width, (b) gravel bar widths and (c) ratio of gravel bar width to wetted channel width.



the maximum active width of the sedimentation zone (Figure 5.2b). This indicates that significant quantities of the sediment present in these zones is derived from sediment transfers down the trunk channel of the catchment. However, the expected diminution in the sediment load of the trunk channel due to losses to sedimentation (storage) within these reaches appears to be replenished by inputs from tributaries downstream. There are a number of secondary peaks in channel width within sedimentation zones downstream from confluences. Tributary streams are therefore important sources of bed load for the trunk channel, which enables a repeating pattern of sedimentation zones to develop.

The ratio of active gravel width to wetted channel width along the channel allows the significance of gravel bars to be assessed (Figure 5.2c). The ratios remove the effect of the general downstream widening trend resulting from the contribution of flow from successive tributaries. A ratio of one indicates bars are equal in width to the wetted channel, a ratio of greater than one represents the magnitude by which bar width exceeds wetted channel width. The ratios indicate the relative importance of sedimentation zones and reveal that these may be defined as reaches with bar widths greater than three channel widths. There are a number of exceptions such as between 14 and 15 km, which is not defined as a sedimentation zone, because the persistence of a high ratio is not maintained after 1856. At 27 km the short but wide bar is associated with a tributary confluence. Six sedimentation zones have been identified and each changed over the period 1856-1991.

The channel composition in 1896 (Figure 5.3 and 5.4a) was very similar to that of 1856. The channel was still characterised by the large gravel bars (Figure 5.3) that produced an irregular total channel width structure (Figure 5.2a). Five of the six sedimentation zones were characterised by extensive bars with the exception of that between 15 and 17 km, which was reduced in size (Figure 5.2b). The ratio of active gravel to wetted channel reveals that this sedimentation zone was now characterised by bars less than three times wetted channel width, and as a result the total channel width declined in this location (Figure 5.5). The ratio of active bars to the wetted channel increased between 22 and 25 km but declined in significance between 28 and 30 km (Figure 5.2c and 5.4c). However, these correspond with only relatively modest changes in channel width (Figure 5.5). Changes in active bar to wetted channel ratios between 22 and 25 km and 28 and 30 km were accomplished by changes in either active width or wetted width; between 22 and 25 km the wetted

Figure 5.3 Channel width structure of the River Wear in 1896

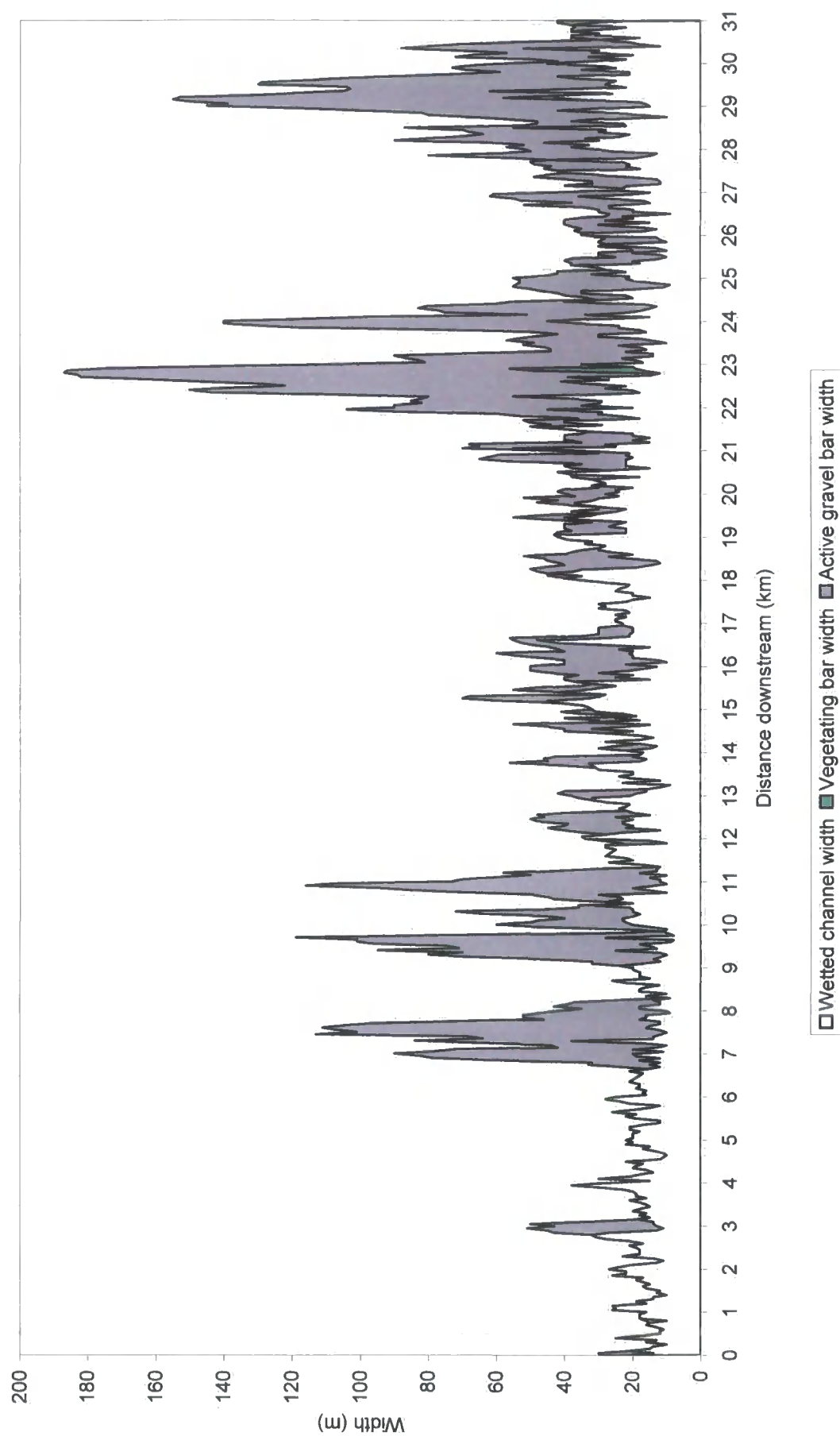


Figure 5.4 Channel structure during 1896, (a) total channel width, (b) gravel bar widths and (c) ratio of gravel bar width to wetted channel width

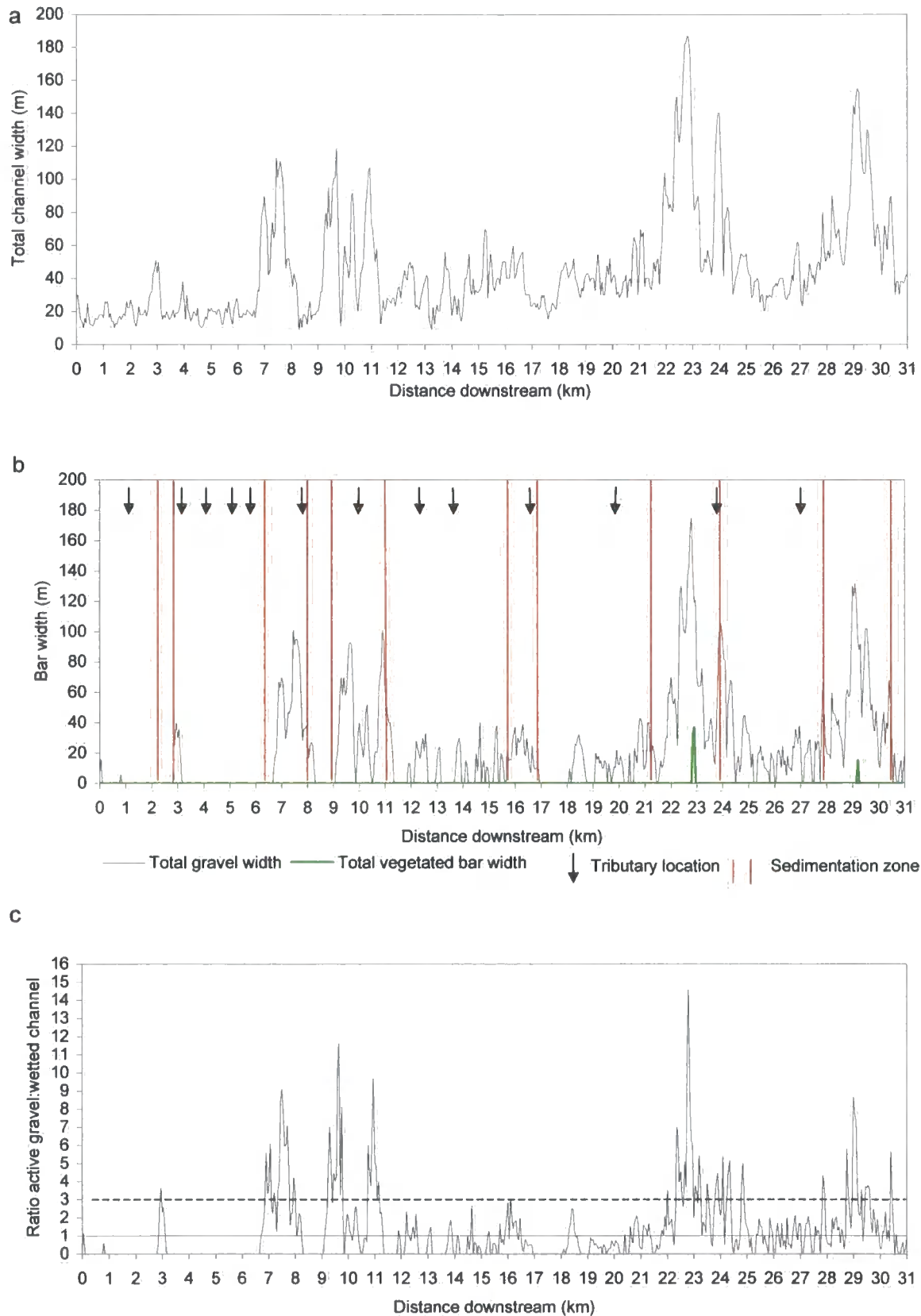
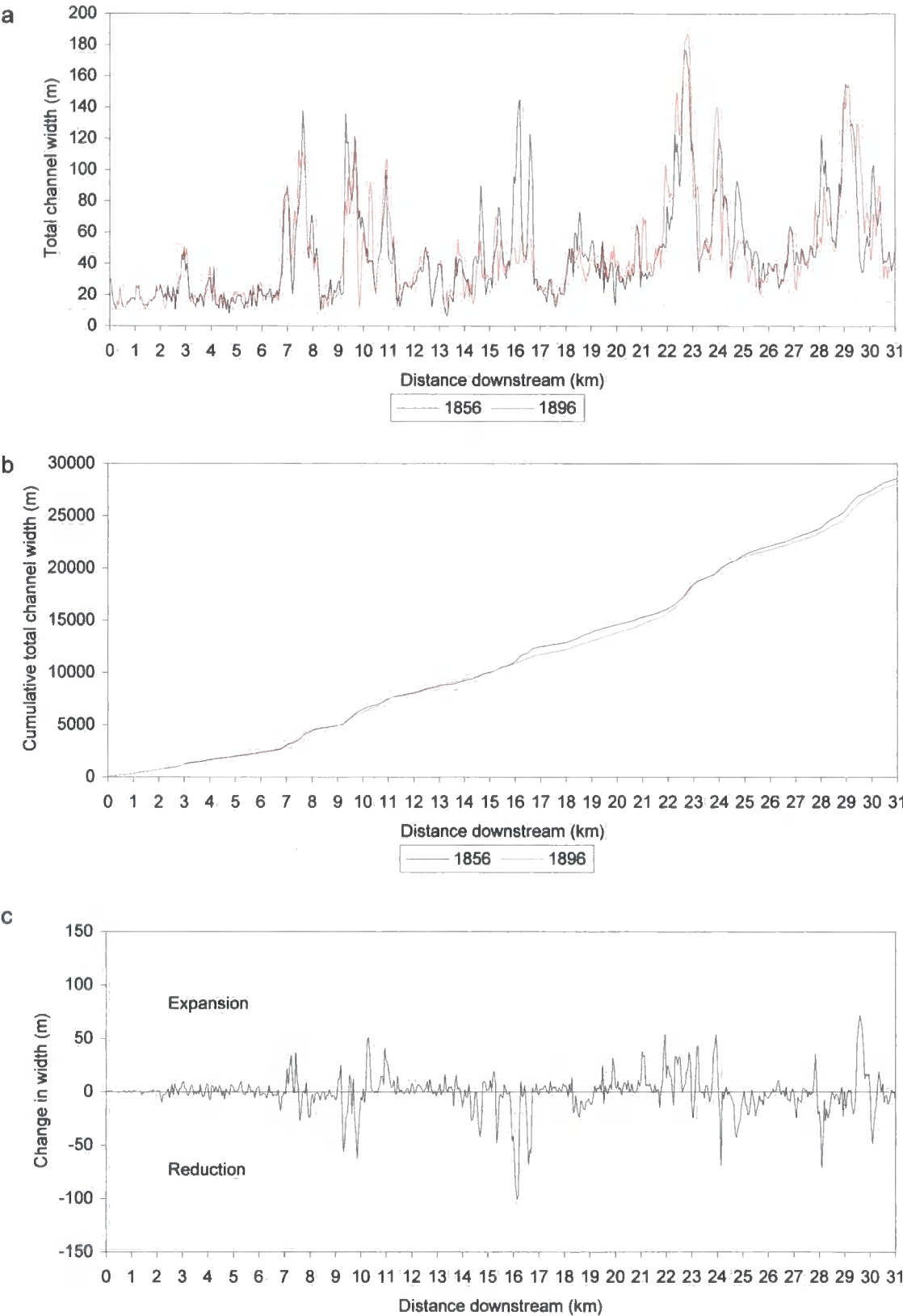


Figure 5.5 Total channel width (a) compared for 1856 and 1896, (b) cumulative channel width for 1856 and 1896 and (c) change in total channel width 1856-1896.



width declined while active gravel area increased, but the converse happened between 28 and 30 km (Figure 5.6). This minimised the changes in the total channel width. However changes around 16 km were associated with both declines in gravel bar width and the wetted channel width (Figure 5.6), resulting in a change to the total channel width (Figure 5.5). Differences in the stage of the wetted channel between the two years can be ruled out as the cause of these changes because a systematic increase or decrease in wetted channel width does not occur along the channel. Changes in wetted channel width appear to reflect changes in the dimensions of the wetted channel within the active channel belt, such as the alternation between multiple and single thread sections. Generally, significant fluctuations in the width of the active channel such as between 7 and 8 km, 16 and 17 km and between 28 and 30 km are co-incident with the sedimentation zones (Figure 5.2b). Changes in the width of both the wetted channel and active gravel bar reflect changes in channel planform, which confirms the dynamic nature of the channel in these locations.

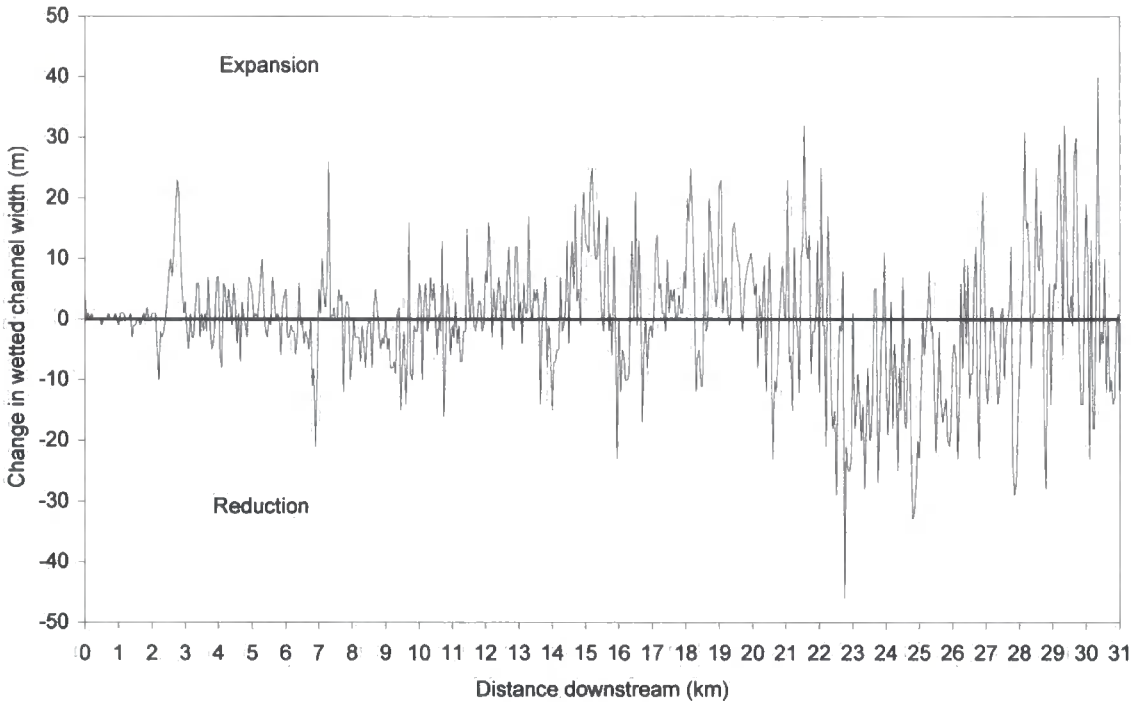
The results from Chapter 4 indicated sedimentation in the lower catchment may have occurred as a result of the downstream migration of a pulse of sediment generated in the upper catchment. The decline in gravel widths upstream of 20 km and increases downstream appear to support this, however with the exception of changes between 16 and 17 km the magnitude of such changes are small. Additionally widening occurs downstream from narrowing, which may indicate local sediment transfers. Increases in gravel extent downstream from 20 km (Figure 5.5 b and 5.6b) appear to represent a shift in the location of sedimentation from 14-20 km where a decline in bar area is occurring. Importantly, the reaches where these increases in active bar width occurred in the lower catchment already had wide active channels. This suggests that sedimentation began in the lower catchment prior to 1856, with sedimentation between 1856 and 1896 involving mainly local transfers.

5.2.2 1896-1951

The broad structure of the channel in 1951 is similar to that of 1896 with frequent gravel bars and discrete reaches showing extensive gravel bars (Figure 5.7). Some small gravel bars formed between 0 and 7 km although this is in part a function of the increased detection rate of gravel bars achievable on aerial photographs. There are nine short reaches (totalling 3.8 km) where data is absent due to the presence of dense tree cover which obscured the channel on the aerial photographs. This has a

Figure 5.6 Change in (a) wetted channel width and (b) active bar width between 1856 and 1896. Negative values indicate a reduction in width.

a



b

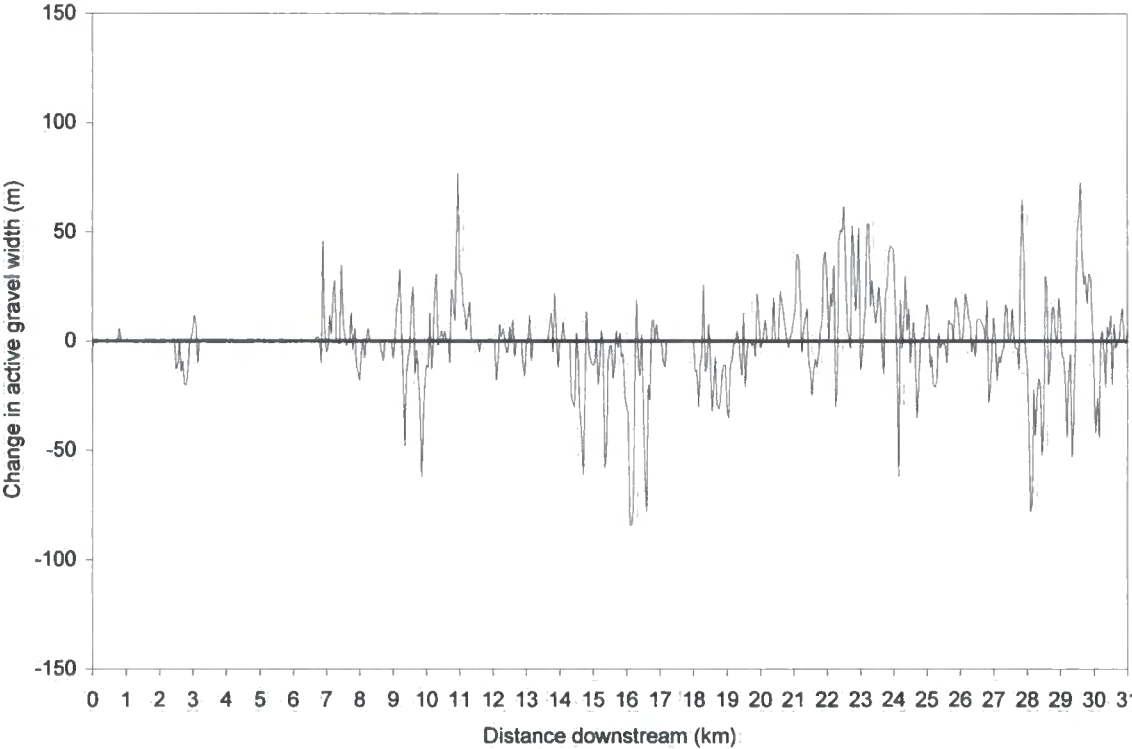
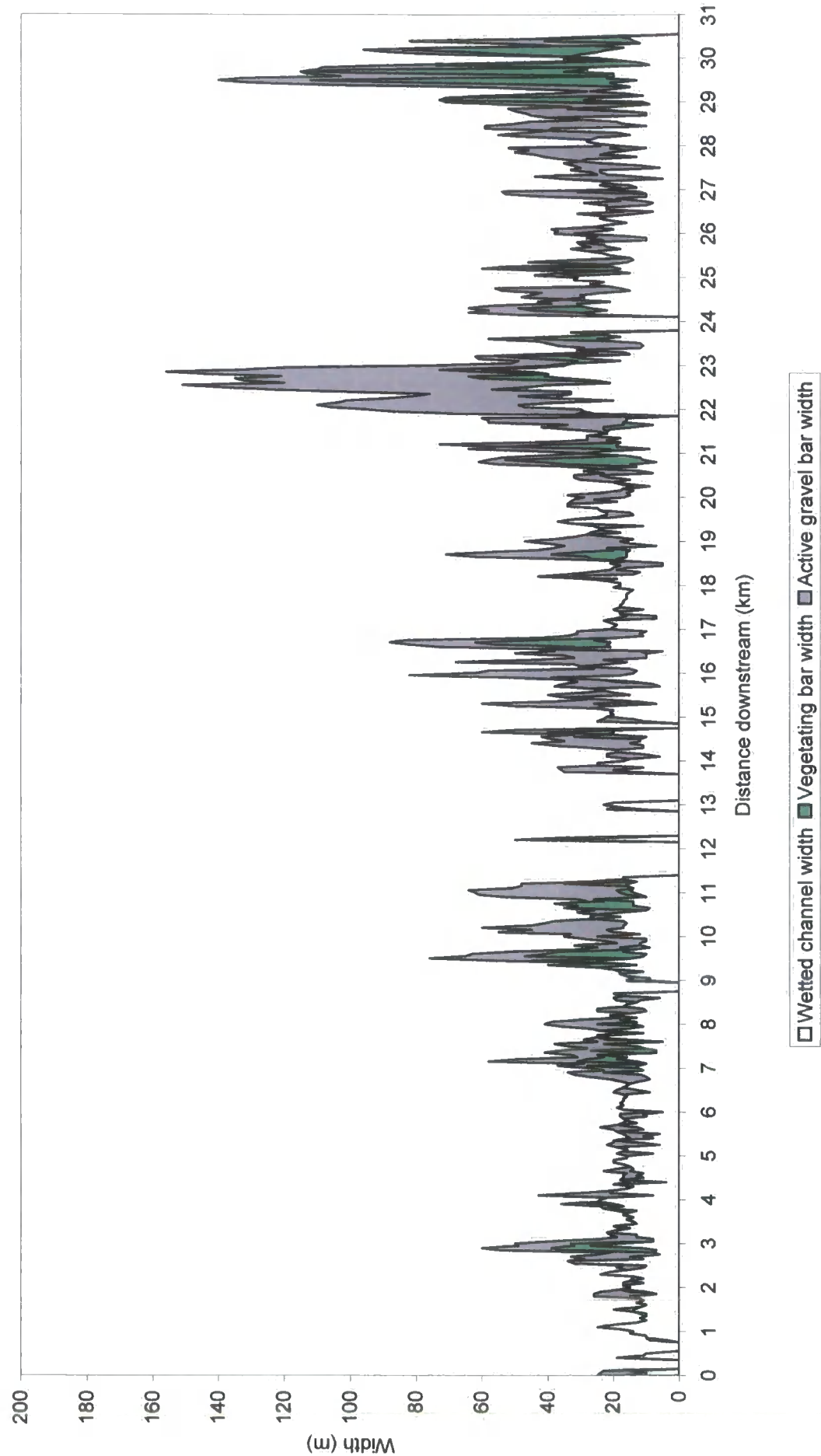


Figure 5.7 Channel width structure of the River Wear in 1951.



minimal impact on the analysis, because these are locations of planform stability with few bars. Indeed it is this planform stability that has enabled the growth of trees.

The channel is still characterised by large variations in the total channel width (Figure 5.7 and 5.8a). The sedimentation zones are discernable in the bar width plots, however the majority have shown a decline in size, and vegetating bars form a significant proportion of the bars in these reaches (Figures 5.7 and 5.8b). The ratio of active gravel to wetted channel reveals that gravel area has declined considerably in all the sedimentation zones (Figure 5.8c). It is the vegetating gravel bars in the majority of the sedimentation zones that maintain the wide channel widths relative to surrounding reaches; this demonstrates the role of vegetation colonisation in reducing active width (Figure 5.7). For example vegetation colonisation greatly reduced the active width of the channel between 28 and 31 km. Here much of the wide total width is composed of vegetating bars, the active width having fallen dramatically (Figure 5.8). The change in total channel width (Figure 5.9) reveals that the gross channel form is simplifying in a downstream direction. Changes in channel width are particularly significant between 7 and 11 km, which has resulted in a flattening of the cumulative channel width curve (Figure 5.9b). These changes represent large declines in active gravel.

The reach between 22 and 24 km remains important; the increase in cumulative channel width in this location in 1951 was almost as great as in 1896 (Figure 5.9b). In this location active gravel had declined significantly, the wide channel width being maintained by an increase in wetted channel width (Figure 5.10). The large decline in gravel width at 29 km was not accompanied by such an increase in wetted channel, but reflected vegetation colonisation. The reach between 22 and 24 km appears to have been behaving differently from the rest of the trunk channel at this time. The only significant sedimentation during this time period occurred between 16 and 17 km and was coincident with a decline in the wetted channel width (Figure 5.10b). This sedimentation might have been related to the downstream transfer of sedimentation from the channel between 13 and 16 km.

Figure 5.8 Channel structure during 1951, (a) total channel width, (b) gravel bar widths and (c) ratio of gravel bar width to wetted channel width.

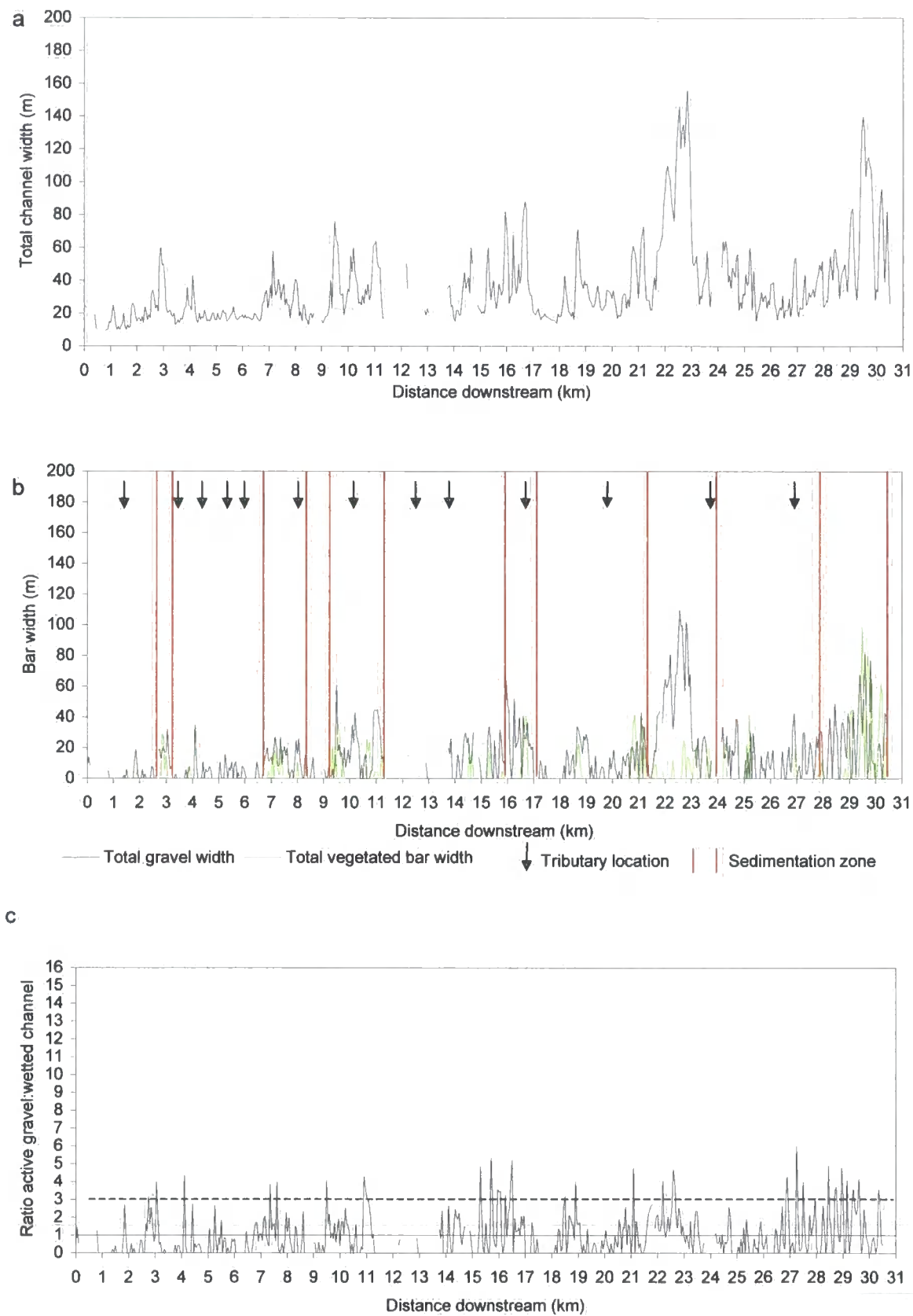


Figure 5.9 Total channel width (a) compared for 1896 and 1951, (b) cumulative channel width for 1896 and 1951 and (c) change in total channel width 1896-1951.

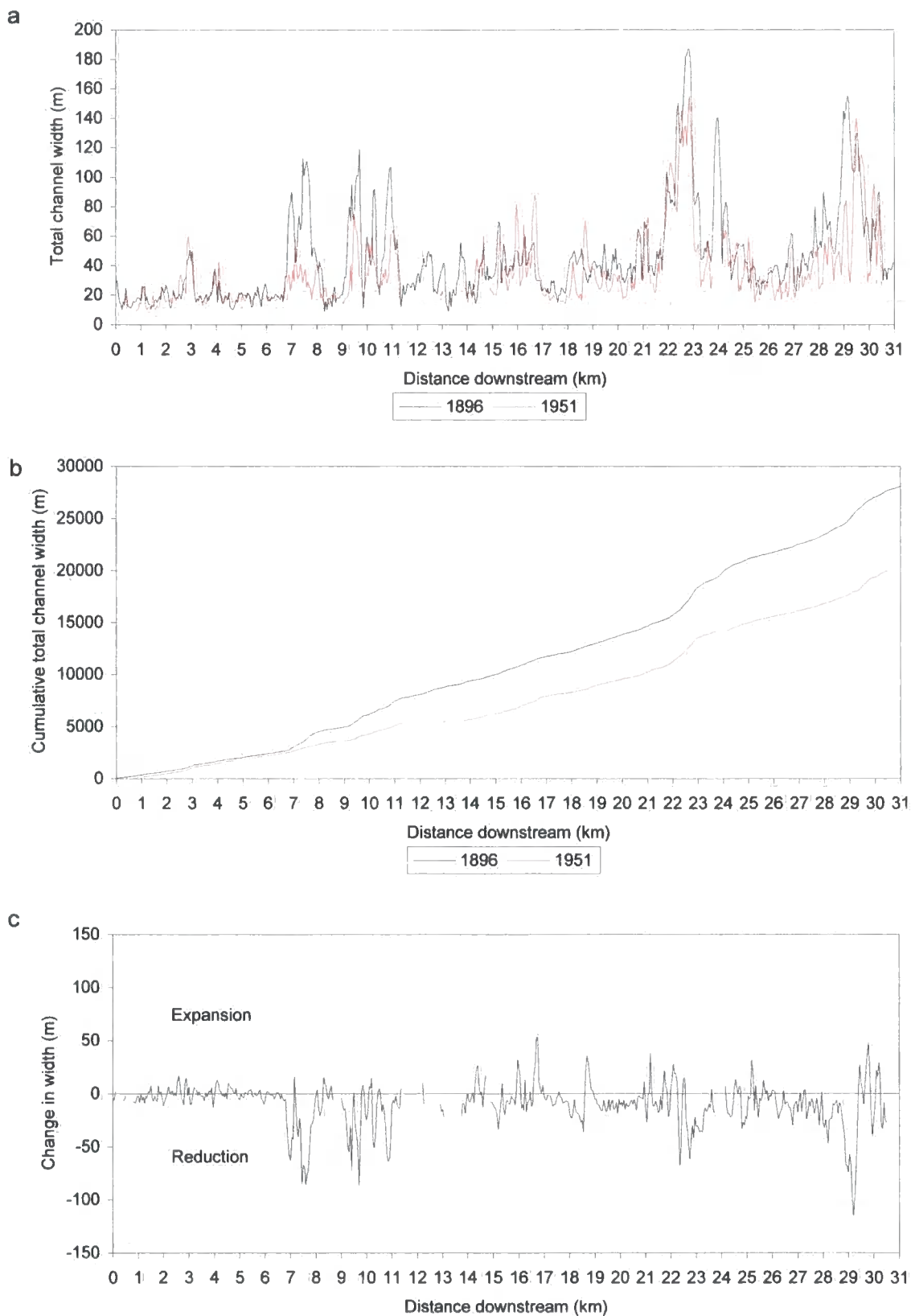
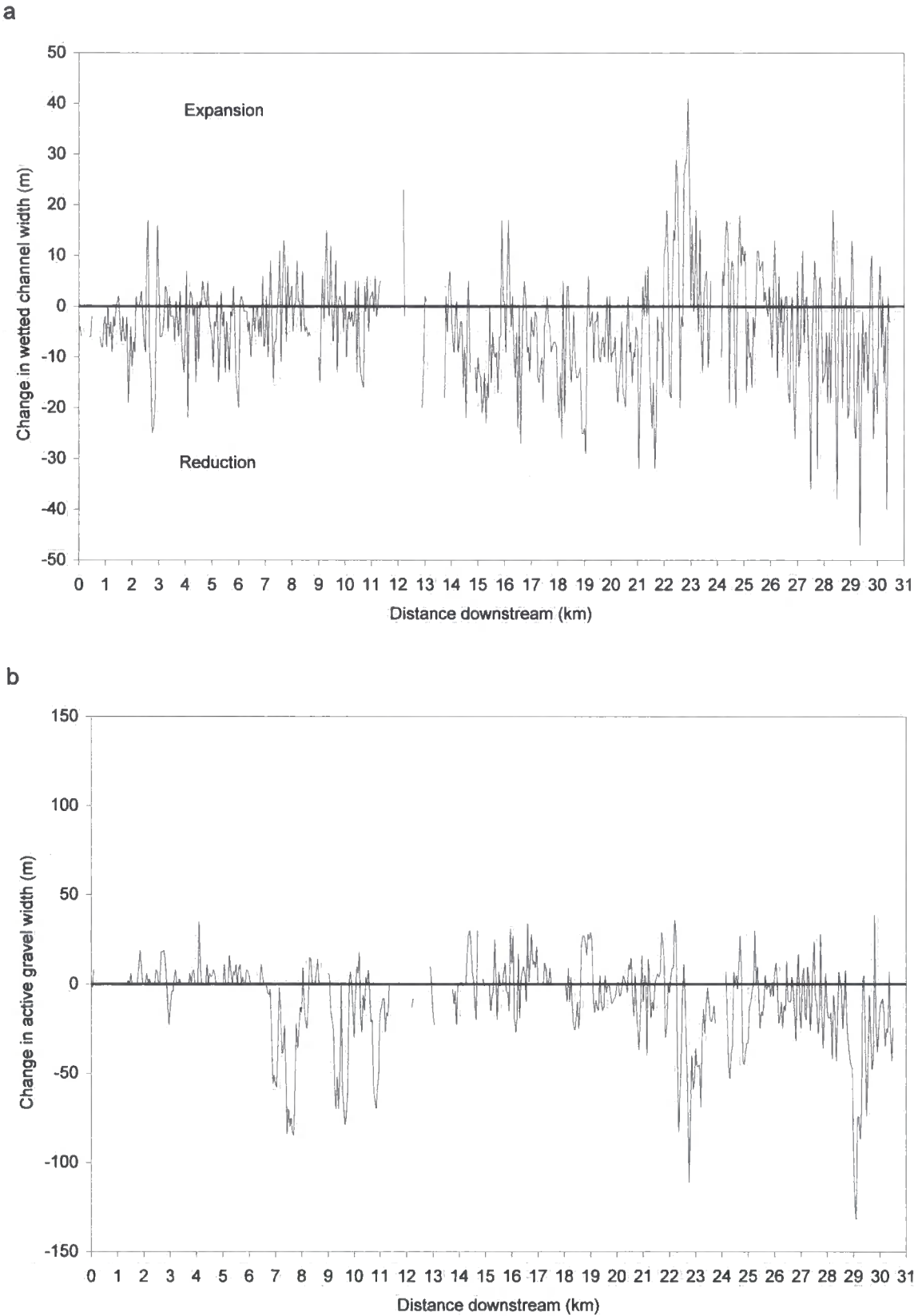


Figure 5.10 Change in (a) wetted channel width and (b) active bar width (b) between 1896 and 1951. Negative values indicate a reduction in width.



5.2.3. 1951- 1991

The channel in 1991 was characterised by small, evenly distributed gravel bars and represents a marked contrast to the previous years (Figure 5.11). The total channel width, while irregular, was not characterised by the large variations typical of previous years (Figure 5.12a). Again some data is missing due to the presence of trees (total of 4 km), but this does not significantly detract from the results. Sedimentation zones are not clearly discernable from the intervening reaches (Figure 5.12b) and nowhere along the channel do bars exceed three wetted channel widths (Figure 5.12c). The total channel width contrasts markedly with that of 1951 (Figure 5.13a) and the cumulative channel width now rises steadily with no jumps in contrast to previous years, which were characterised by distinct sedimentation zones. There were a few small increases in total channel width, however these are insignificant in comparison to the decline which occurred, the most notable of which occurred at 22-23 km and 29-30 km (Figure 5.13c). Generally these changes reflect changes in the active bar width (Figure 4.14b). The wetted channel width is highly variable although a significant decline occurred between 22 and 24 km, because this site was characterised by an anomalously wide wetted channel width in 1951.

Figure 5.11 Channel width structure of the River Wear in 1991.

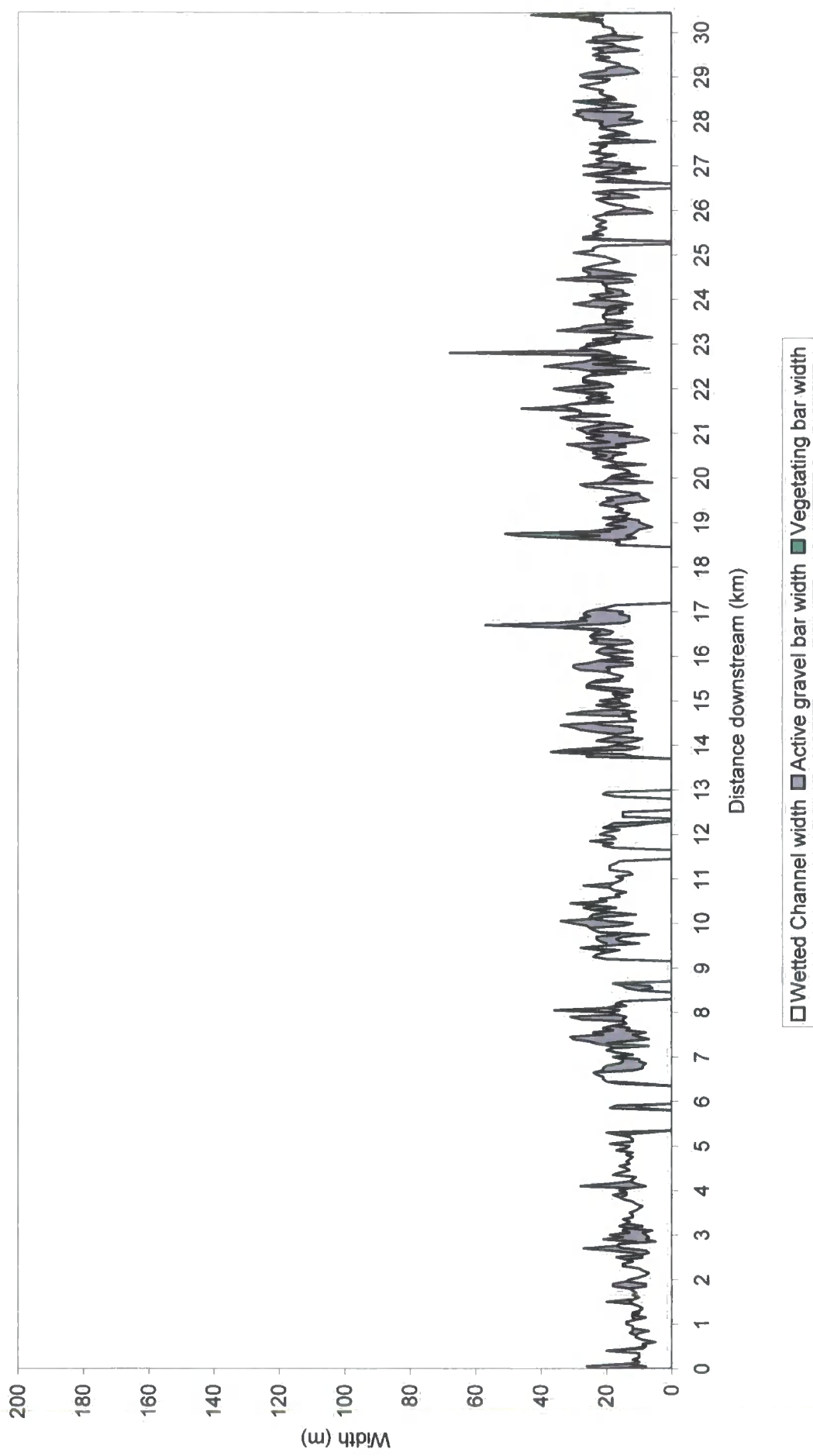


Figure 5.12 Channel structure during 1991, (a) total channel width, (b) gravel bar widths (b) and (c) ratio of gravel bar width to wetted channel width.

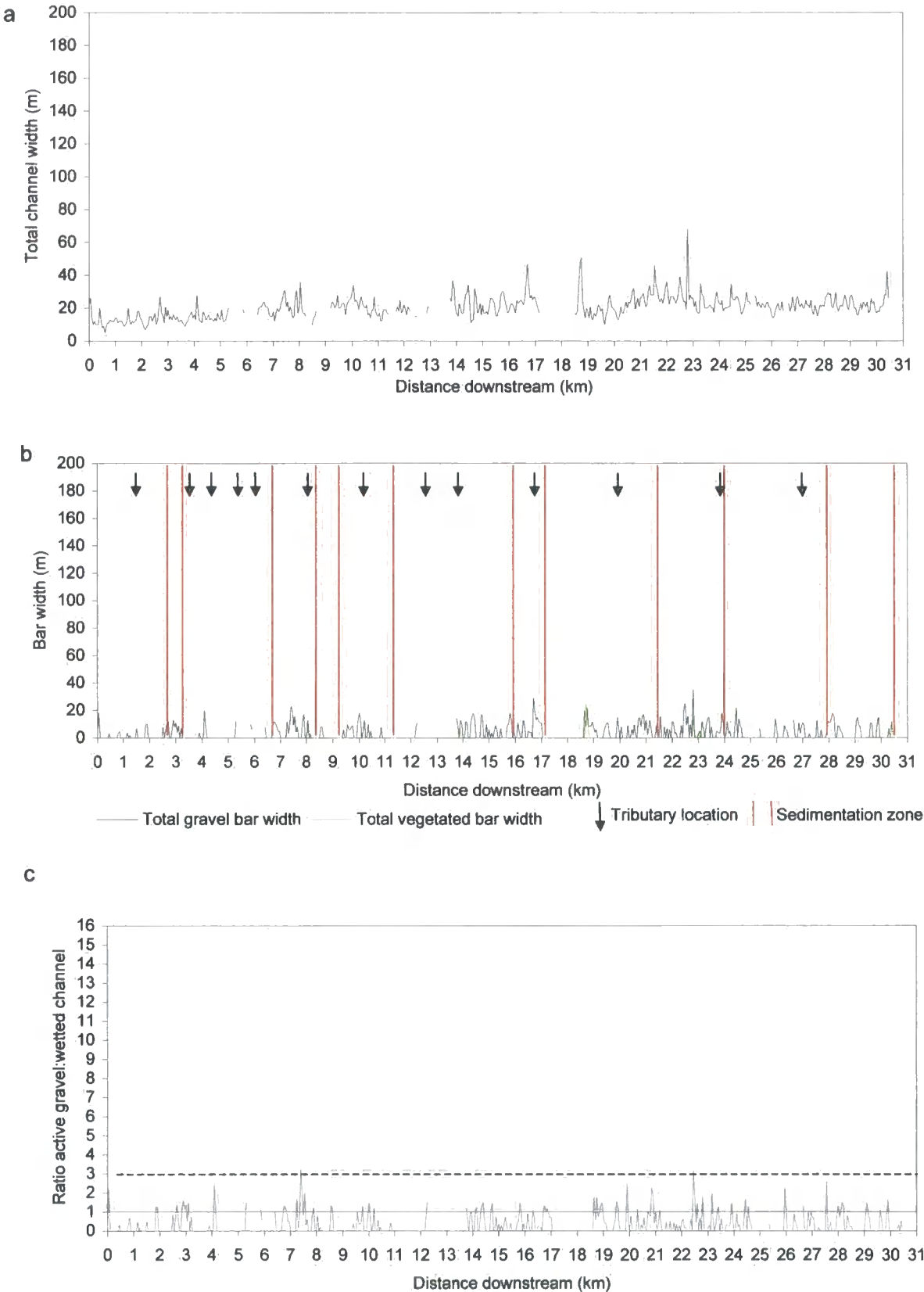


Figure 5.13 Total channel width (a) compared for 1951 and 1991, (b) cumulative channel width for 1951 and 1991 and (c) change in total channel width 1951-1991.

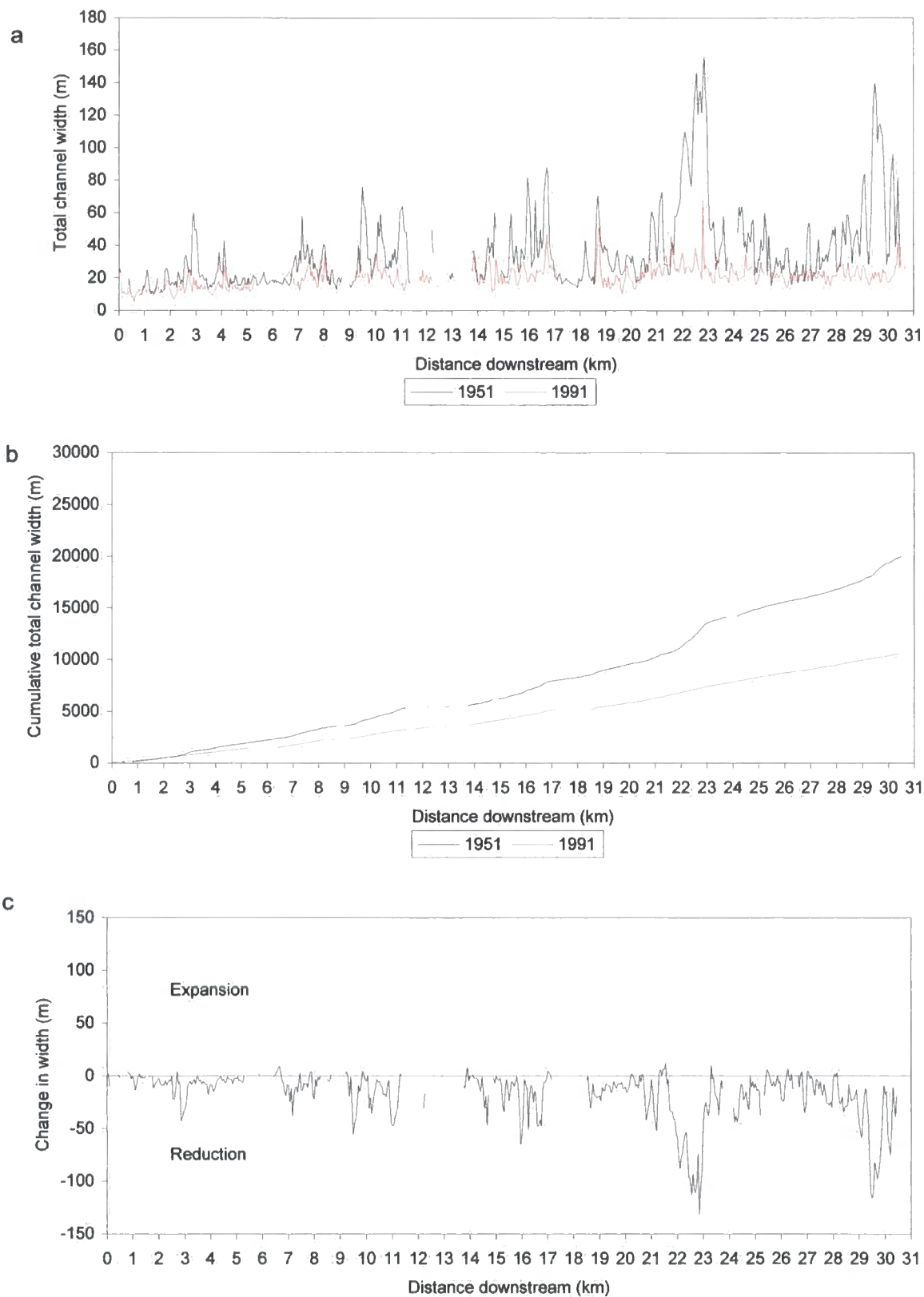
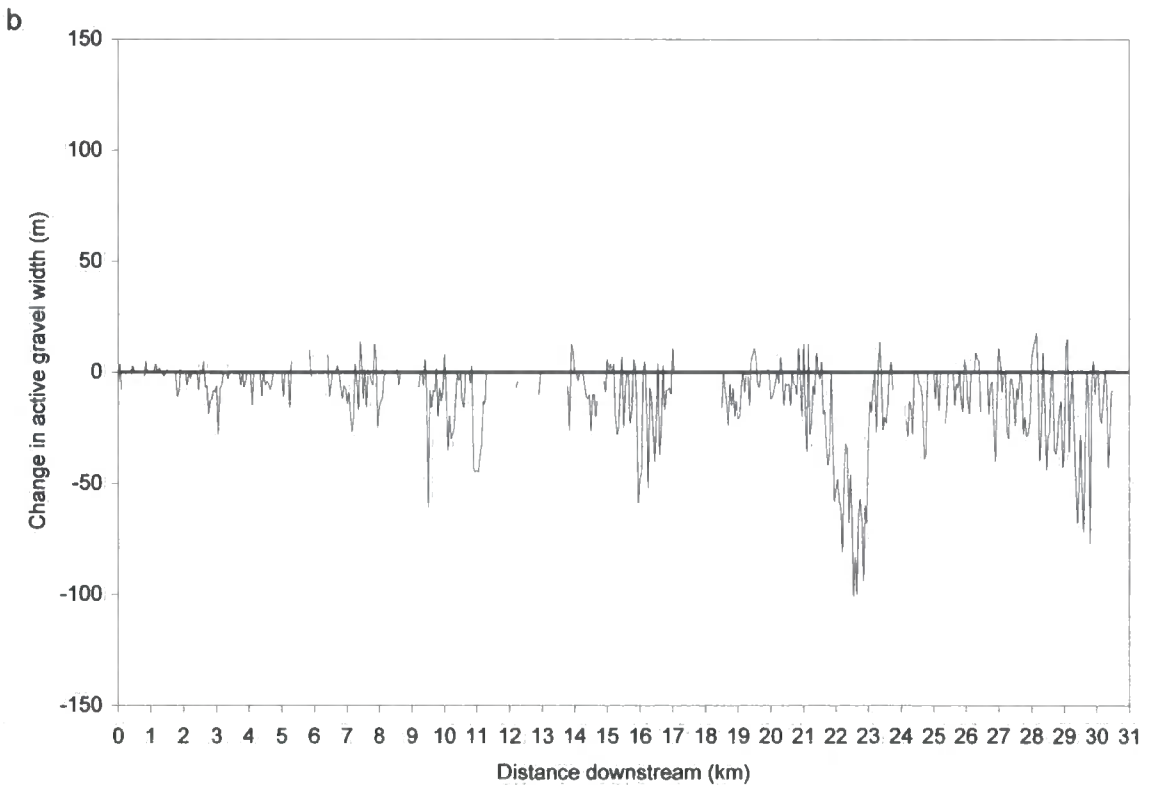
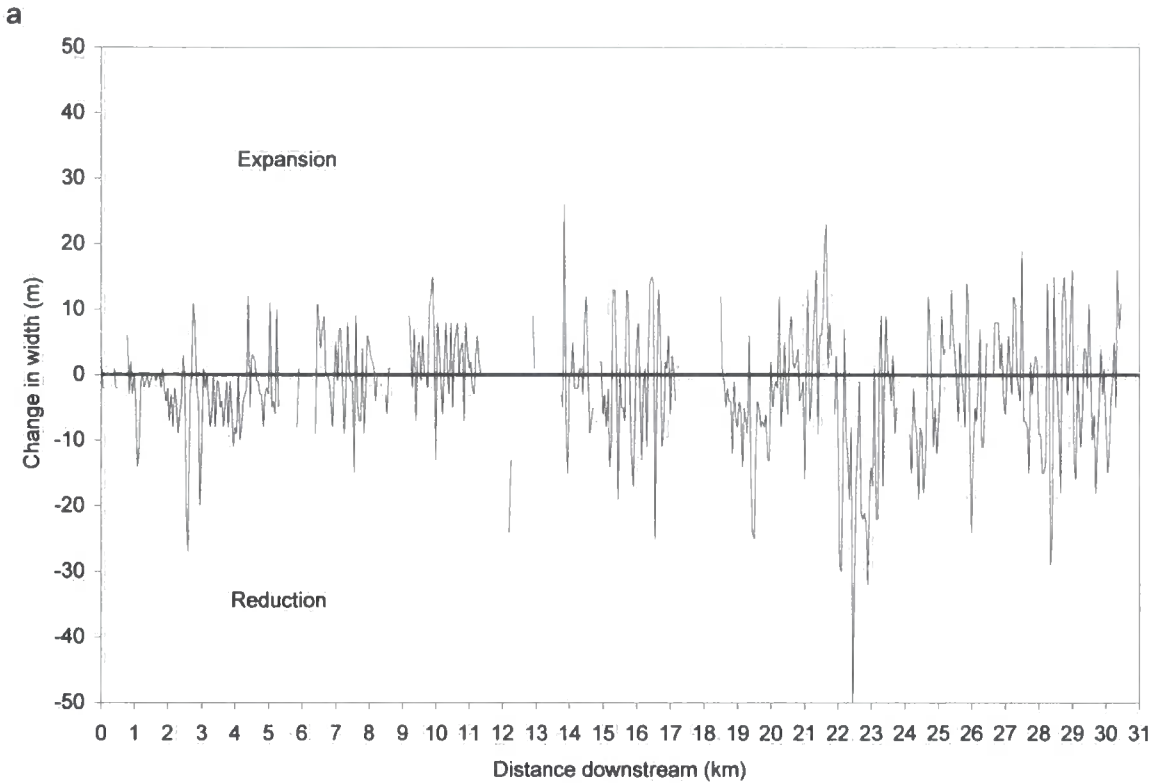


Figure 5.14 Change in wetted channel width (a) and active bar width (b) between 1951 and 1991. Negative values indicate a reduction in width.



5.3.4. Summary

Changes in channel structure during the study period were dominated by changes in the size of the gravel bars located along the channel, and despite some local variations the dominant trend was for a decline in the extent of gravel bars. The river channel in 1856 was characterised by six sedimentation zones located relatively evenly along the length of the trunk channel, separated by reaches containing smaller gravel bars (Figure 5.15a). The channel structure in 1856 was very similar to that of 1896, however declines in the extent of the gravel bars occurred in sedimentation zones 3, 4 and 5. Locally this decline was so large that by 1896 the sedimentation zone 4 was barely distinguishable from the intervening reaches (Figure 5.15b). Increases in gravel bars in the lower sedimentation zones were far less marked between 1856 and 1896 than the decline upstream. By 1951 the gravel bars of zones 2,3 and 6 had decreased substantially with zone 5 experiencing a smaller decline. However, sedimentation zones 1 and 4 showed a slight increase in extent. By 1991 the sedimentation zones had ceased to be discernable from the intervening reaches and the gravel bar extent in the intervening reaches also declined markedly. The changes in total channel width during each of the three time intervals are summarised in Figure 5.16. This confirms the dominance of declines in channel width during the study period, primarily through declines in gravel bar extent, particularly between 1951-1991. Total channel width is a particularly useful indicator of channel structure in a given year as it combines both wetted channel and both active and vegetating gravel bars. For this reason total channel width has been selected for further analysis.

Figure 5.15 Channel width structure of the River Wear during 1856 (a), 1896 (b), 1951 (c) and 1991 (d). Sedimentation zones are numbered 1- 6.

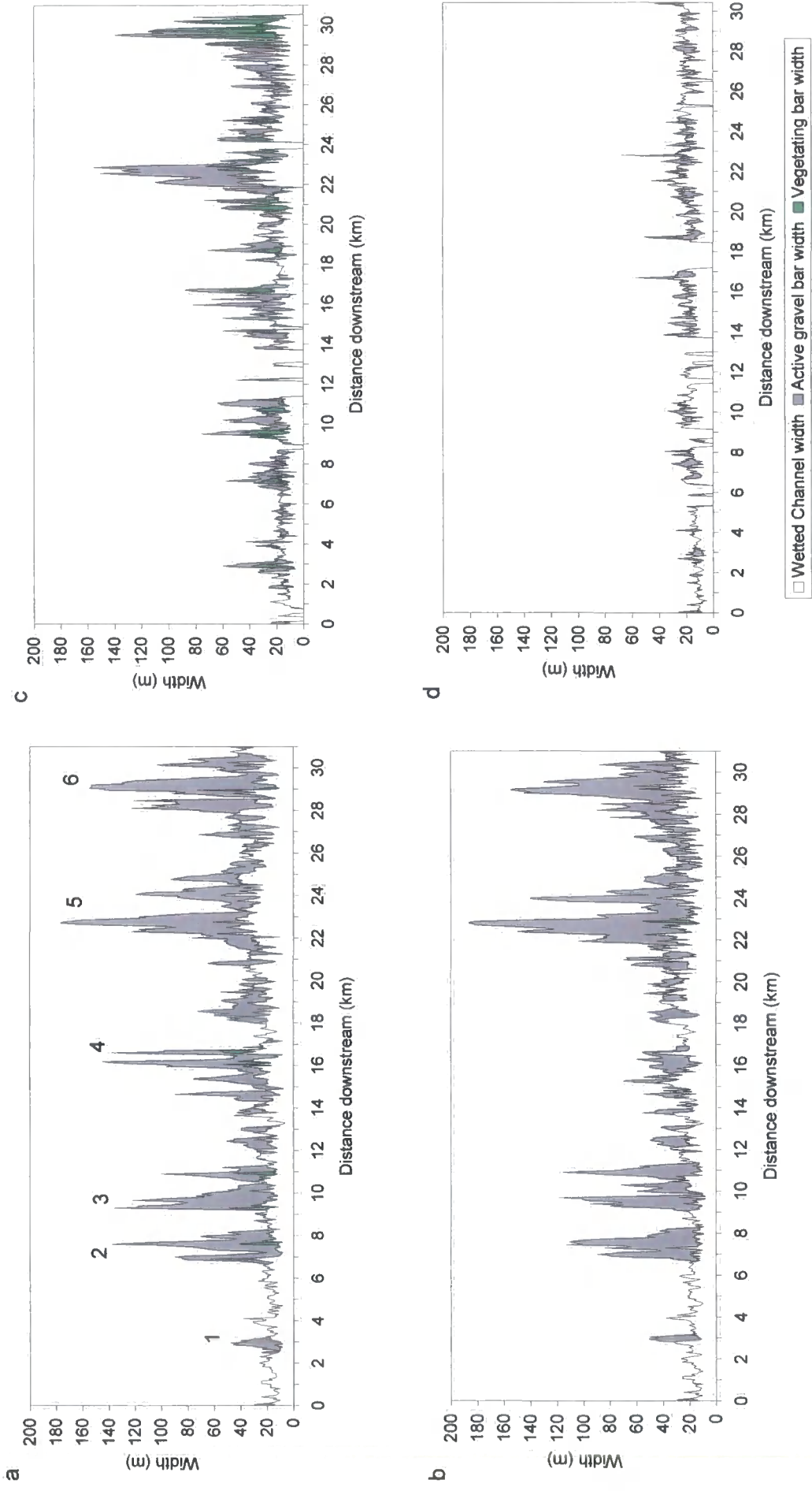
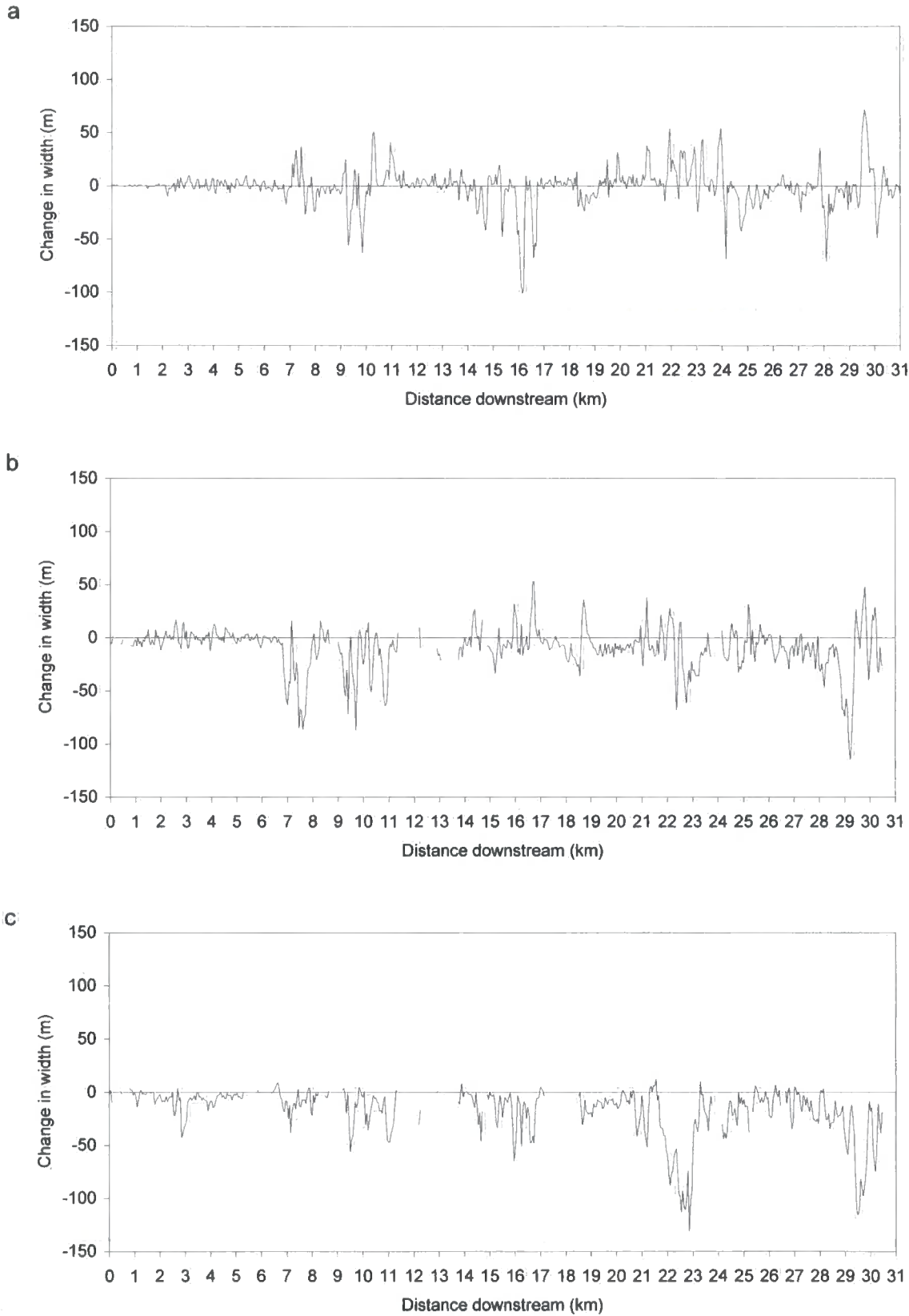


Figure 5.16 Change in total channel width (a) 1856-1896, (b) 1896-1951 and (c) 1951-1991.



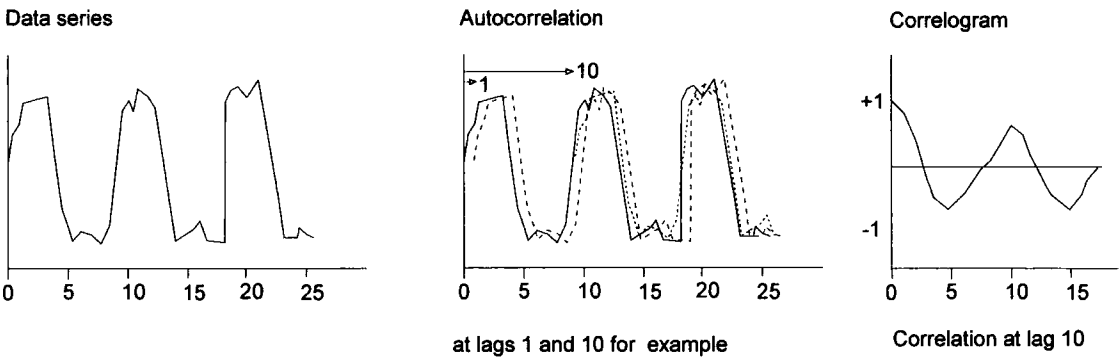
5.3.5 Time series analysis

Time series analysis provides a useful statistical technique which allows continuous sequences of data, such as the channel width series, to be summarised and compared in a rigorous manner. The technique is appropriate in this instance because the width series appears to be characterised by regular and systematic variations that may be statistically significant. Time series techniques can determine whether there are cyclical patterns within a data sequence and how these patterns differ between series. The technique offers the potential to determine any regular width structure inherent to the river channel, which might explain the location of sedimentation zones. Also, comparing time series may indicate downstream migration of channel structure as a result of sediment transfer. The width series data consist of a range of planform elements such as active gravel bars, vegetating bars and wetted channel width, recorded at 50 metre intervals. The results described in the preceding section indicated that total channel width summarises the main patterns of change. Total channel width has therefore been selected for time series analysis.

There are a wide range of time series techniques available (Davis, 1986) and for the purposes of this analysis three techniques have been selected: autocorrelation, spectral analysis and cross-correlation. Autocorrelation is a measure of self-similarity within a sequence of data (Figure 5.17a). A sequence of data is compared to itself at successive lags along the series; for example, an autocorrelation at a lag of one compares the whole data set with itself offset by one point down the series (Figure 7.17a), at a lag of two each point is compared to that two points down the series and so on. Conventionally autocorrelation is not calculated for lags greater than one quarter of the length of the data set (Davis, 1986). Autocorrelation enables regular repetitions (such as peaks in channel width) in the data set to be detected. The results of the autocorrelation analysis are plotted on a correlogram which indicates the degree of correlation at successive lags (Figure 5.17a). The example used in Figure 7.17a shows a positive correlation at 10 lags, although this is not a perfect correlation (it is less than +1) due to small variations within the cyclic trend in the series. The nature of variations such as this can be examined using spectral analysis.

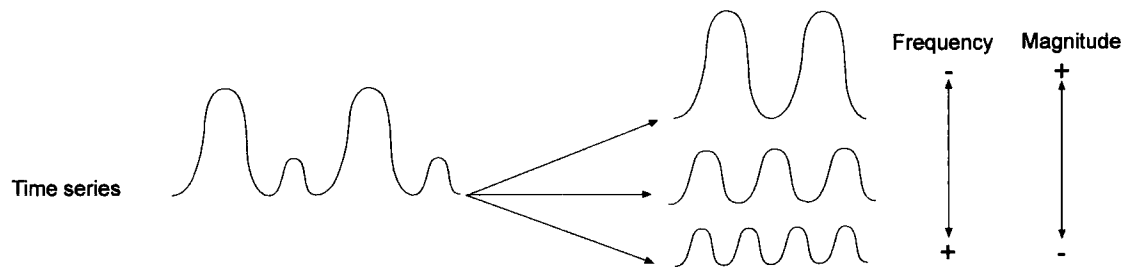
Figure 5.17 Schematic diagram illustrating idealised time series and the result of (a) Autocorrelation and (b) Spectral analysis.

a Autocorrelation

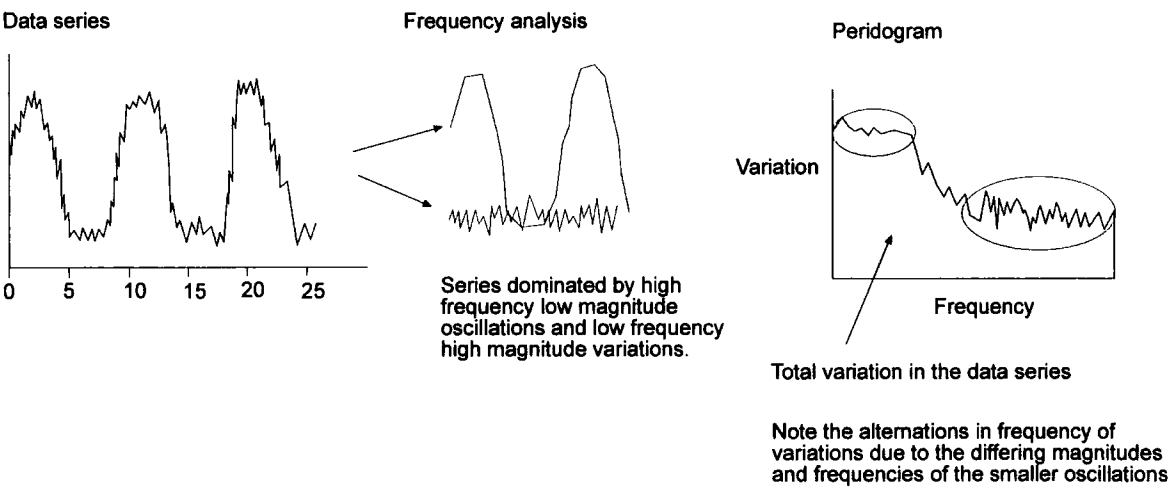


b Spectral analysis

Time series can be divided into individual components based on wave length and amplitude



Actual data sets can be more complex



Spectral analysis is used to quantify both the frequency and duration of variation within a time series. In the context of this study the magnitude and frequency of variations in the channel width and how this has changed through time is of particular interest. Time series, such as the channel width series, can be regarded as a continuous sequence of data which can be divided into a series of components known as frequency bands (Figure 5.17b) (the frequency at which a variation occurs). The result is plotted on a chart known as a peridogram and is referred to as the spectral density function. Figure 5.17b illustrates this. Here the data set consists of two main components, a high magnitude but low frequency variation and a low magnitude but high frequency oscillation. The peridogram depicts this as high variations at low frequencies and low variations at high frequencies. However the result is complicated by the fact that neither of the two main components is composed of the regular variations in the idealised example (Figure 5.17b). There is a lack of regularity in the size and duration of variations in the data; instead the data is composed of many components, each with slightly differing magnitudes and frequencies, and this complicates the peridogram. Nevertheless there are two distinct regions, which reflect the general structure of the data (Figure 5.17). The area beneath the line of the peridogram represents the total variation in the data series, while the line of the plot shows the frequency of variations in the data set. This is useful as it enables the significance of the peaks in the data series to be determined. This curve may also be plotted cumulatively, as a cumulative spectral distribution function. Plotting the result in this manner removes the complexity of the spectral density plot.

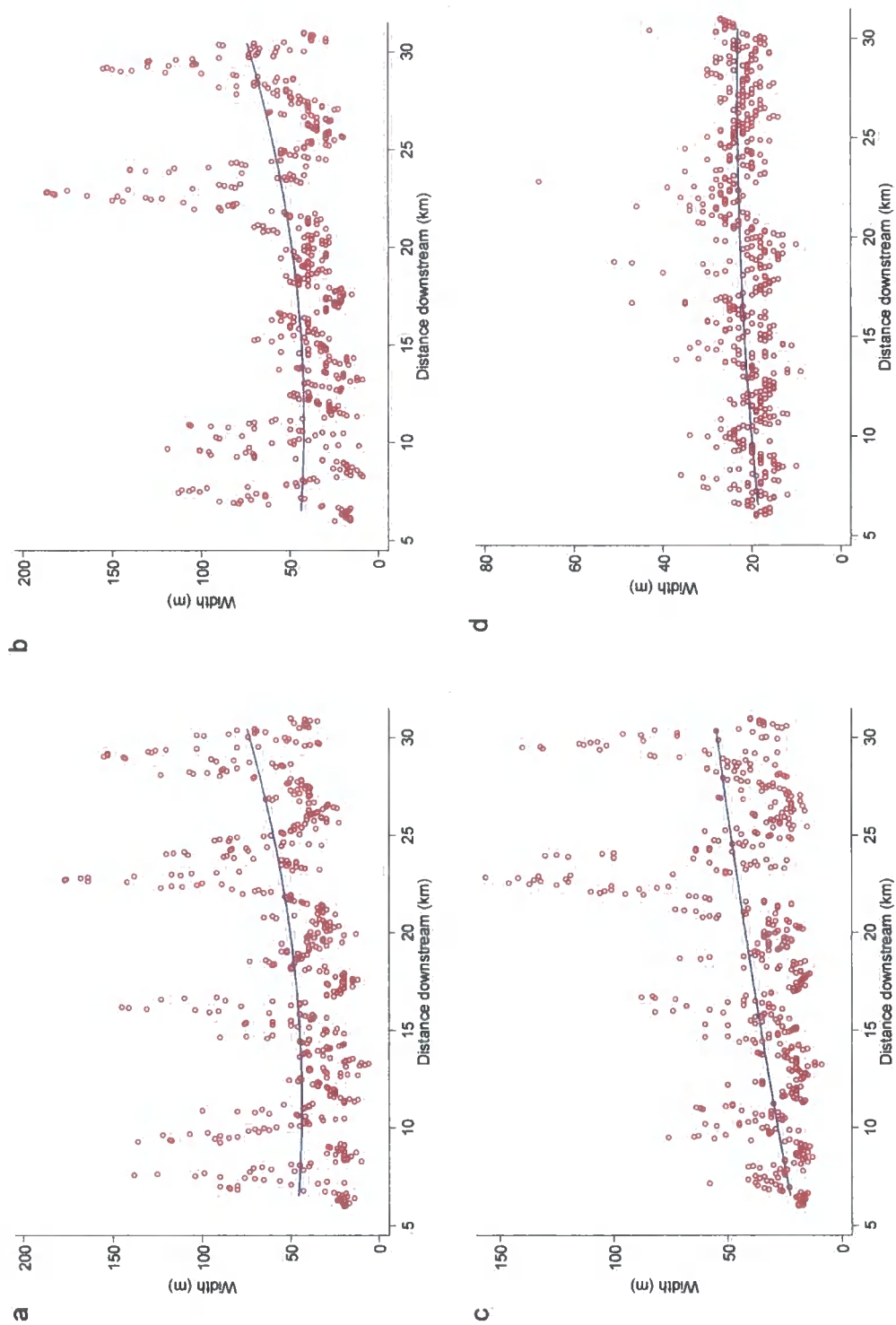
Cross-correlation provides a technique for comparing two time series and is based on the same principles as autocorrelation. As with autocorrelation the correspondence between two series is determined at successive positions or lags along the time series. This is particularly useful for this study because it allows downstream migration of channel structure to be identified. Cross-correlations are plotted on cross-correlograms. Because either of the two time series can lead the other, cross-correlations are plotted at both positive and negative lags. For example a positive lag reflects the first series being compared at successive lags down the second series. This indicates the degree to which the first series (1856) matches the second (1896) at successive lags, enabling the downstream migration of channel structure to be detected. At negative lags the second series is compared at successive lags down the first series. This indicates the degree to which the second series matches the first at successive points downstream; in the context of rivers this

is unlikely to be significant. Cross-correlograms are not symmetrical unless the two data series being examined are identical.

Time series analysis can be susceptible to trends in data. The Weardale datasets show two potentially problematic characteristics. First there is a pronounced increase in the average channel width after 6 km due to an increase in the frequency and extent of gravel bars, a reflection of bedrock confinement in the upper reaches. This persistent narrow section, which is uncharacteristic of the data series as a whole, may distort the time series analysis. As such the first 6 km of data was excluded from the time series analysis. Secondly, despite the high variation in channel width there is a general trend for downstream widening as an increasing number of tributaries join to the channel. Trends such as this reduce the sensitivity of autocorrelation to periodicity in the data series (Davis, 1986). In order to remove this trend a regression curve was fitted to each data series and time series analysis conducted on the residuals. Quadratic, rather than simple linear regression was found to be the best method of representing the trends in the series (Figure 5.18).

Gaps in a dataset, such as the short gaps in the 1951 and 1991 series (total of 4 km), can influence the time series analysis, particularly with respect to patterns in the alternation of wide and narrow reaches. This is likely to be particularly significant when the complete sequences are compared to the incomplete sequences. As a result width data was interpolated to fill these gaps in the data sets. Interpolations were based on observations from the aerial photographs, the nearest known channel widths upstream and downstream, and from channel widths recorded on earlier surveys. As the missing channel widths were a result of trees lining the riverbanks the approximate channel width could be interpolated with relative ease. The channel margin is likely to be just off centre (toward the channel) from the centre of a particular tree. This was confirmed by field investigations and observations from aerial photographs where isolated trees occur, which revealed that the trunks are located close to the bank top. Channel widths estimated on the basis of this interpolation technique provide a more accurate estimate of channel width than simple linear or rectangular interpolation techniques based only on measurements upstream and downstream. However gravel bar widths cannot be reconstructed using this technique, because their presence cannot be confirmed where the channel is completely obscured. In practice this is not significant as the time series analysis undertaken here only examines total channel width.

Figure 5.18 Quadratic regression of total width for (a) 1856, (b) 1896, (c) 1951 and (d) 1991.



The autocorrelations of total width for the River Wear for 1856 and 1896 (Figure 5.19a,b) reveal a decline in the autocorrelations at successive lags. This indicates that channel widths are relatively persistent and they do not vary dramatically over short distances. This appears to reflect the relatively persistent nature of both the wide sedimentation zones and narrow intervening reaches. This was slightly more pronounced during 1896. There are no secondary peaks, which indicates that the wide sedimentation zones do not occur at regular intervals. The autocorrelation for 1951 (Figure 5.19c) is similar to that of 1896, however there is a minor secondary peak at 14 lags, which suggests a weak periodicity at 700m. This was produced by the decline in the difference between the sedimentation zones and the intervening channel (Figure 5.16c) causing alternations between wide and narrow reaches to be more consistent in magnitude than during earlier years. The frequency of peaks and troughs of similar magnitudes was such that some weak periodicity was likely to be detected. The 1991 plot (Figure 5.19d) is more complex. Generally this reveals that channel widths do not correlate strongly at lags greater than two, and even at lag one the correlation is weaker than those of earlier years. This reflects an increase in the significance of minor peaks as the large changes in channel width no longer occurred (Figure 5.16d). The weak periodicity that appears to exist at around 11 and 17 lags, reflects the rapid variation between the relatively wide and narrow reaches (Figure 5.16d). Autocorrelations calculated for lags greater than 40 revealed no additional detail indicating that computing autocorrelations up to a lag of 40 (representing 2 km of river channel) was sufficient to detect the presence of any structure in the data set.

The spectral density functions are very similar for the years 1856, 1896 and 1951 (Figure 5.20a-c) and indicate that relatively small variations in channel widths are more frequent than the large variations that occur over longer distances (lower frequencies). This means that the variation in channel width is greater over long distances (low frequency) than short distances (high frequency), which are characterised by relatively small variations in top width. There is however considerable variability in the width data at both low and high frequencies, leading to a complex peridogram. This reflects the fact that the time series is made up of many spectral components rather than a small number of regular waves. Generally the difference between the widest reaches and narrowest reaches is greater than the variation within either of the two channel types. This trend is not as apparent in 1991 which reveals a relatively small change in channel width variation as frequency of variation increases (Figure 5.20d). This indicates that the wide sedimentation zones

Figure 5.19 Autocorrelations of de-trended total width (residuals from quadratic regression) for (a) 1856, (b) 1896, (c) 1951 and (d) 1991.

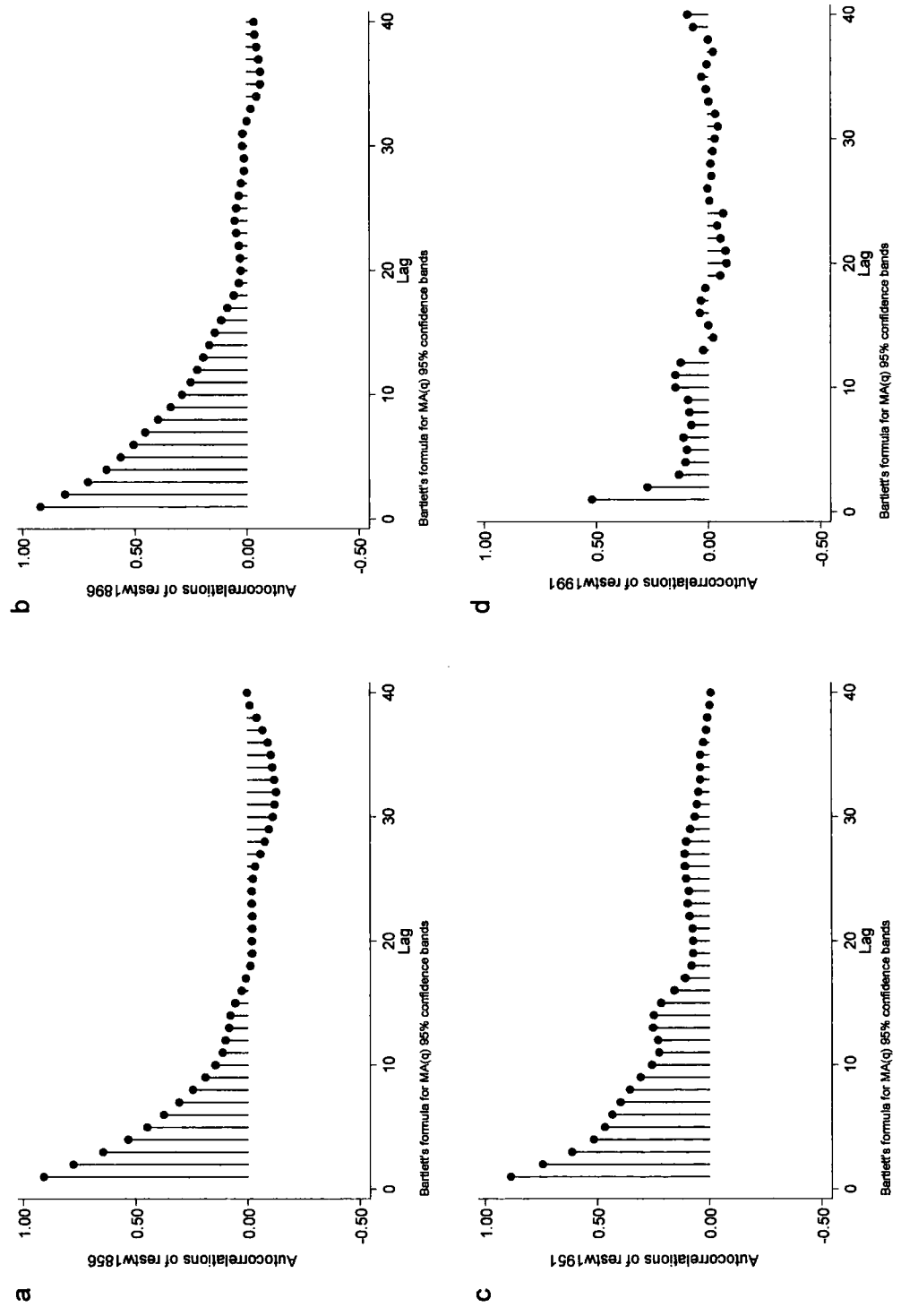
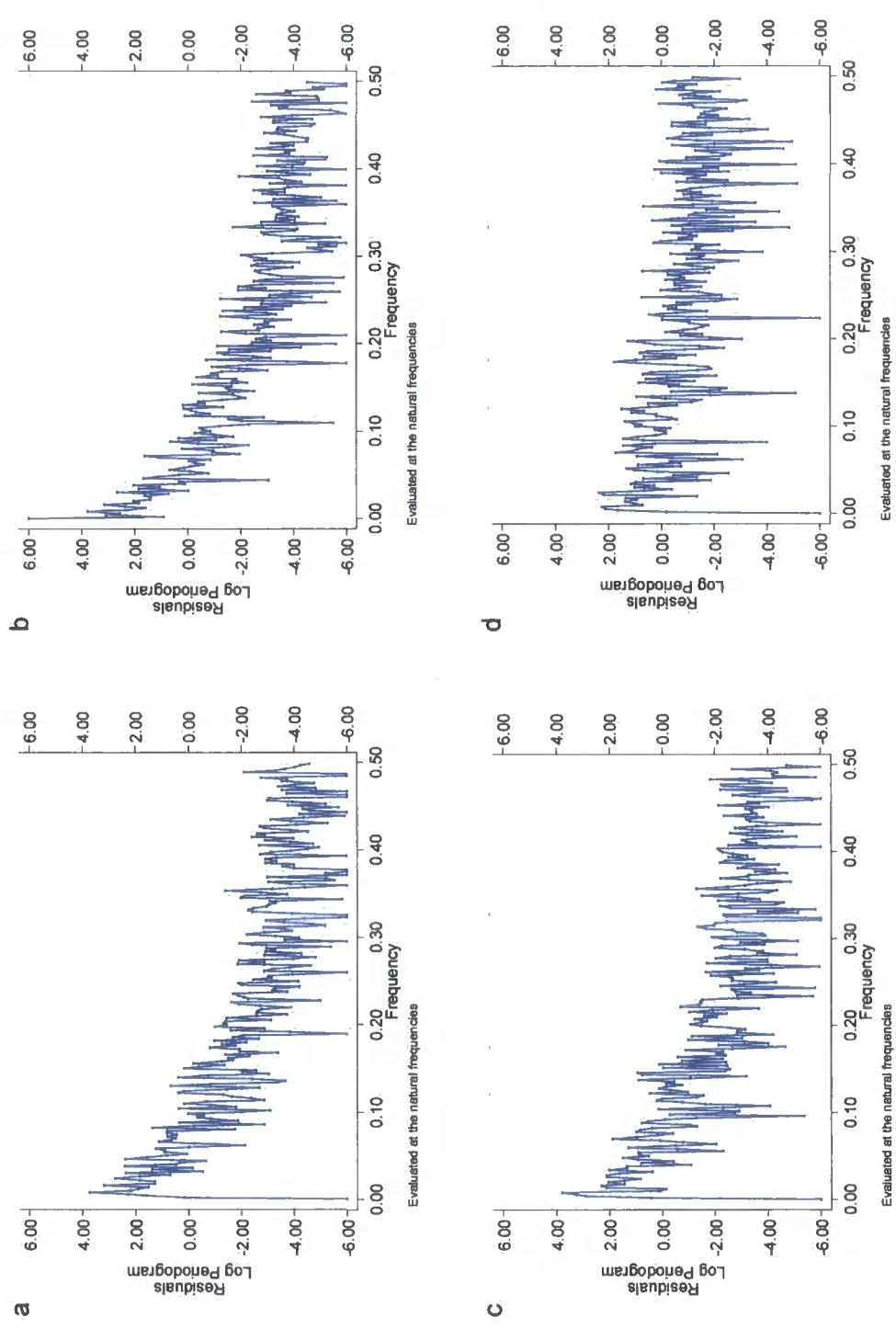


Figure 5.20 Spectral density function of de-trended total width (residuals from quadratic regression) for (a) 1856, (b) 1896, (c) 1951 and (d) 1991.



(high variability) are no longer a dominant component of the channel planform.

This is confirmed by the cumulative spectral density functions (Figure 5.21). In detail these reveal that wide widths were very slightly more significant during 1896 than 1856, (the curve is steeper) and that by 1951 these wide widths had decreased in significance (shallower curve) although this was not particularly marked. By 1991 however (Figure 5.21d) the curve has reduced greatly and large channel widths are no longer as important. While these results appear simply to reaffirm the conclusions reached by visual examination of the raw width plots, the relatively small variation between the 1896 and 1951 curves reveals that sedimentation zones were still important components of the channel structure during 1951 despite significant declines in their extent.

Cross correlations between width 1856 and 1896 and 1896 and 1951 width series show good correlations at lag zero (Figures 5.22a,b), indicating that these series are relatively similar. This similarity is greatest between the 1856 and 1896 plots, which show a relatively high degree of symmetry, reflecting the close correspondence in channel structure. The 1951-1991 cross correlation (Figure 5.22c) shows a lower but nevertheless significant correlation at lag zero, indicating some similarity in the two time series despite the declines in the extent of gravel bars during this period. This indicates that in 1991 the larger bars were concentrated in the location of the former sedimentation zones. No clear cross-correlations with increasing lag occur during any of the time intervals (Figure 5.22) indicating that no significant systematic downstream migration in channel structure could be detected during any of the time intervals. However this does not rule out local changes because the cross correlation looks at the whole time series at once and repeats the calculation through 40 lags. In order for downstream shifts to be detected the whole time series examined would have to shift, and not just individual sections.

Figure 5.21 Cumulative spectral density function of de-trended total width (residuals from quadratic regression) for (a) 1856, (b) 1896, (c) 1951 and (d) 1991.

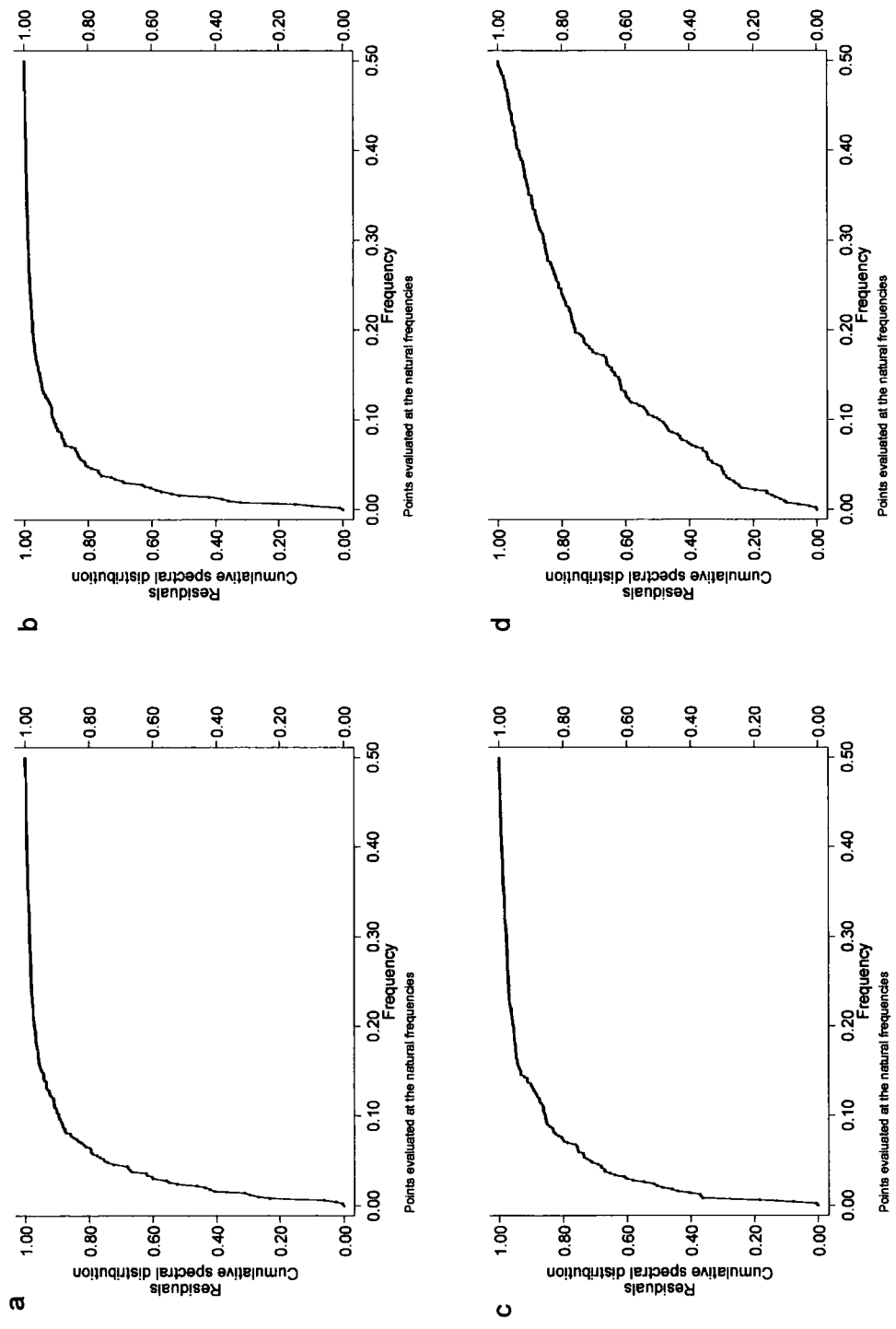
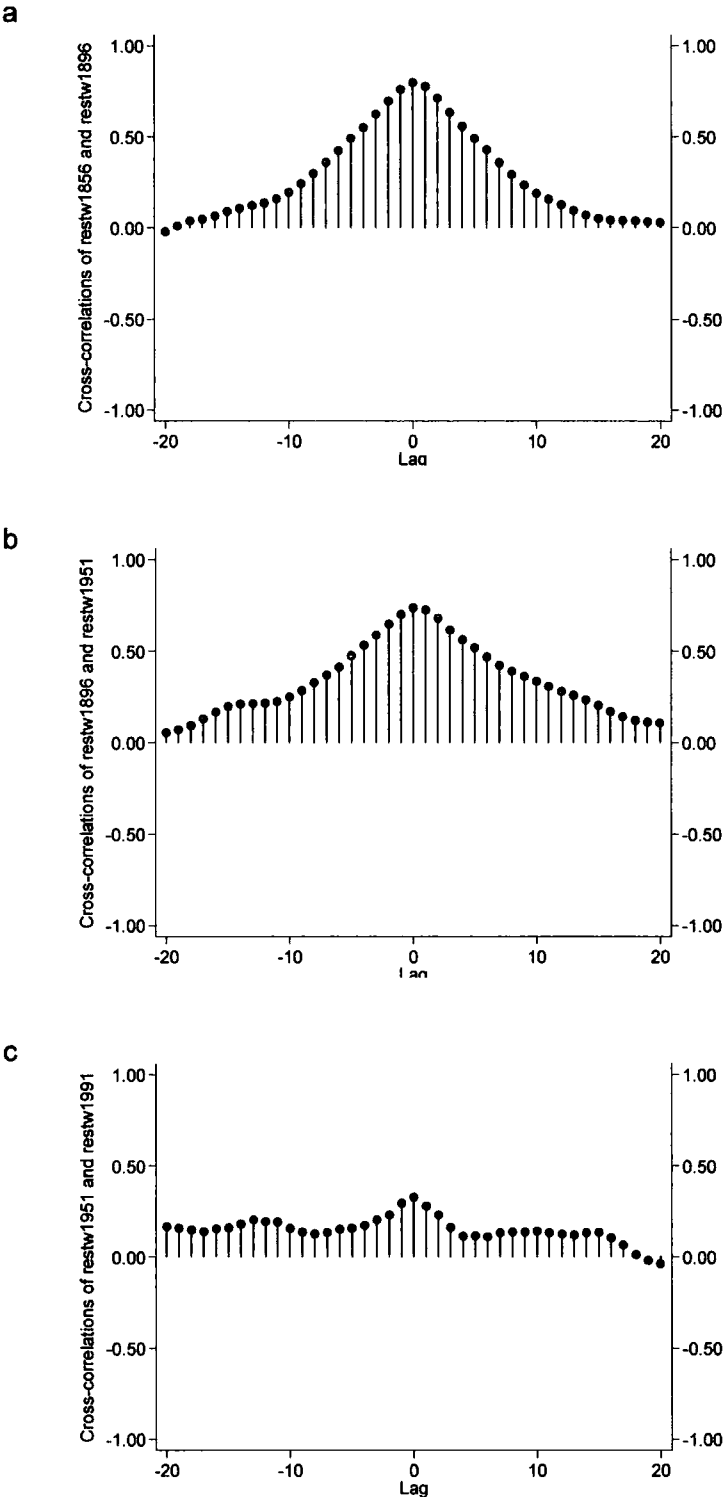


Figure 5.22 Cross-correlation of de-trended total width (residuals from quadratic regression) for (a) 1856-1896, (b) 1896-1951, (c) 1951-1991.



5.3. Trunk channel behaviour 1856-1991

The catchment scale investigations described in chapter 4 indicated that between 1856 and 1896 the upper catchment, including the upper trunk channel, was characterised by a decline in the extent of the active gravel while the lower reaches of the trunk channel were characterised by increases in the extent of gravel bars. The width series results confirm the declines in the extent of gravel area in the upper reaches of the trunk channel, although the main reductions were concentrated in sedimentation zones 2, 3 and 5. Increases in gravel area in the lower catchment were far less significant than the declines in the upper catchment. Extensive gravel bars were already present in the lower reaches of the trunk channel in 1856 in the form of two large sedimentation zones. As such the downstream migration of a pulse of sedimentation between 1856 and 1896 proposed in chapter 4 is less conclusive and requires re-evaluation. While the decline in gravel extent recorded in the upper catchment was larger than the increases in the lower catchment, there is nevertheless a clear divide between declining gravel bar extents in the upper trunk channel and increasing bar extents in the lower. On the basis of the close relationship between bar area and sedimentation rates, discussed in chapter 4, this is taken to indicate the downstream migration of sedimentation. The relatively small increase in gravel bar area in the lower catchment, in comparison to the size of the bars, suggests this reflects the latter stage of this pulse of sedimentation. The wide gravel bars of sedimentation zones 5 and 6 imply that the main phase of sedimentation occurred earlier in the nineteenth century.

The catchment scale analysis indicates that during the period between 1896-1951 the catchment exhibited a pattern of localised reworking with no consistent zones of decrease or increase in gravel bar area. The width series results for the period 1896 to 1951 also indicate that localised reworking was occurring in the catchment, in particular in the middle reaches of the trunk channel between 14 and 22 km manifested by variations in the channel width (Figure 5.17b). There were however, concentrated declines in the extent of gravel bars between 6 and 12 km and 22 and 30 km. These declines were principally concentrated in the sedimentation zones. Despite these declines the sedimentation zones remained important components of the river channel structure during this period emphasised by the time series analysis, which revealed the gross channel width structure was similar to that of earlier years. The importance of the sedimentation zones is also underlined by the concentration of the greatest change in channel dimensions into these reaches during the period

1896-1951. The changes in channel dimensions were principally driven by vegetation colonisation of wide gravel bars, which had begun to affect the lower catchment by 1896.

A fundamental change in the width structure of the channel occurred between 1951 and 1991. The sedimentation zones that had characterised the catchment since the mid-nineteenth century were completely removed and gravel bars within the intervening reaches also substantially declined in size. This decline in the difference between wide and narrow reaches meant that the frequent, but in historical terms minor, variations in channel width associated with bends, bars and variations in confinement assumed a greater significance. This was clearly detected by the time series analysis, which showed weak periodicity in the width structure. This periodicity is likely to have been a result of the frequent small variations in width, which were so numerous that they were detected by autocorrelations to 40 lags (2km). The low correlation values attest to this, the time series detecting repeating peaks but these were not necessarily of the same magnitude. Interestingly the cross-correlations detected a significant correlation between the 1951 and 1991 width series at lag zero, indicating that the overall channel width structure was of a similar form to that of 1951. This is not obvious from the width plots (Figure 5.16 c, d) but indicates that declines in gravel bar extent were relatively consistent along the channel enabling the general patterns of increases and decreases in channel width to be preserved.

The width series analysis has demonstrated that sedimentation zones represented the most important sections of the river channel during the historic period because the majority of the active gravel along the trunk channel was contained in these reaches. These sedimentation zones resulted in a pattern of alternating wide and narrow reaches. The sedimentation zones varied from 1 to 2 km in length while the intervening reaches were generally around 2 km in length. This downstream persistence of channel widths was clearly evident in the time series analysis. These sedimentation zones are no longer distinguishable in the channel width series. The contrasts in the channel width summary statistics demonstrate the historical significance of sedimentation zones (Table 5.1). Since 1896 there has been a decline in both mean channel width and, more significantly, the standard deviation of mean channel width. The low standard deviation in 1991 in particular demonstrates the impact of the removal of sedimentation zones (Table 5.1). In order to fully appreciate the importance of these sedimentation zones the cause of their formation must be determined. As each of the sedimentation zones were already well developed by

1856, earlier map information is required to constrain the timing of their formation as this may indicate the cause of their formation.

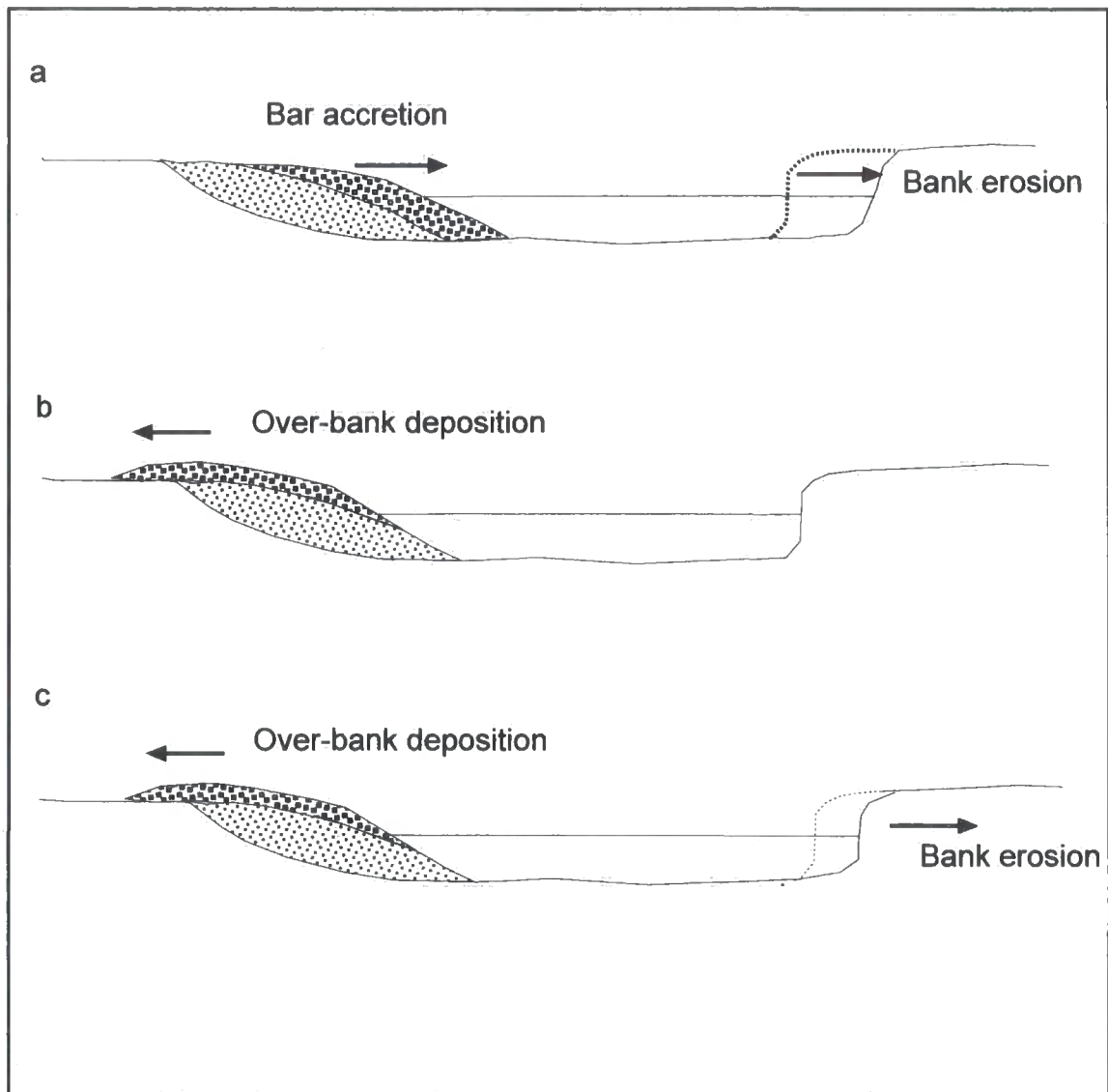
Table 5.1 Channel width series summary statistics illustrating the decline in mean channel width and standard deviation of mean channel width.

	1856	1896	1951	1991
Total width (m)	28627	28081	22197	12634
Mean width (m)	46.10	45.22	35.74	20.35
Standard deviation	31.97	31.47	25.51	6.42

The changes in the flood history of the River Wear between 1800 and 2000 discussed in chapter 4 (Figure 4.8) may provide some important insights into the cause of sedimentation zone development. The mid to late nineteenth century was characterised by a higher flood frequency and magnitude than the twentieth century, which, albeit to a lesser extent, also characterised the early nineteenth century. Large floods may have contributed to the development of wide expanses of gravel in two ways: through increased sediment delivery to the reach and through inundation and reworking of the bar surface which removes colonising vegetation. The large floods of the nineteenth century will have contributed coarse sediment to the channel network through bank erosion (Thorne and Lewin, 1982) or bed incision in the tributary channels (Macklin et al., 1992).

Over the period 1856-1896, particularly between 1856 and 1896, there were numerous examples of increases in the active width of the channel implying locally high bank erosion rates. Yet, widening of the active width may also occur through deposition on the outside of gravel bars during flood events (Figure 5.23). Here coarse sediment is deposited over-bank onto the floodplain; this is most likely to occur where bank heights are low. During flood events widening of the active width may be accomplished by a combination of both over-bank deposition and bank erosion. Significantly, however, the general trend in channel behaviour over the last 150 years has been dominated by declining width and bank erosion appears to have been relatively insignificant between 1856 and 1991. Determining the source of sediment that caused the formation of gravel bars is essential to determining

Figure 5.23 Cartoons illustrating possible mechanisms of active channel widening, (a) bar accretion and erosional response, (b) over-bank deposition and (c) a combination of overbank deposition and bank erosion.



sediment transfers through the catchment, and as a result the cause of channel planform change.

The catchment scale mapping of changes in gravel bar extent (Figure 4.1) indicated that many of the upper tributaries showed a decline in bar area during the nineteenth century coincident with changing metal mining practices. Metal mining operations are known to have provided an important source of coarse sediment (Macklin, 1986), particularly where hushing was employed (Macklin, 1997a). The transfer of coarse sediment from metal mines through the channel network may have been an important cause of the formation of these sedimentation zones. Although uncertainties remain as to whether coarse sediment transfer rates were sufficient given the distances of the lower sedimentation zones from the main sites of mining. It is more likely that metal mining promoted channel planform transformation through the deposition of fine heavy metal contaminated fine sediment which damaged riparian vegetation, leading to bank destabilisation, and also prevented vegetation colonisation of bar surfaces (Macklin and Lewin, 1989, Passmore et al., 1993). Importantly, the lateral deposition of this material will have required large floods.

5.4. Conclusions

- There is evidence of a catchment wide shift in the focus of sedimentation during the nineteenth century, but this appears to have been initiated earlier than 1856.
- Main channel changes between 1856 and 1896 were declines in gravel bar extents in the upper sedimentation zones and slight increases in the lower zones.
- Between 1896 and 1951 some localised re-working occurred in the middle reaches of the trunk channel, but the upper and lower sedimentation zones were characterised by a decline in gravel bar extent. This was largely caused by vegetation colonisation. However gravel bar and wetted channel widths remained anomalously high between 21 and 23 km at this time.
- Over the period 1951-1991 the channel underwent a dramatic decline in the extent of gravel bars. While this appears to have begun prior to 1951, with declines in the extent of the sedimentation zones, these changes represented a fundamental rationalization of channel width structure. This change was the

most significant alteration in the river channel planform to have occurred during the 150 year study period.

- Channel changes appear to have been concentrated into the sedimentation zones between 1856 and 1951, however, between 1951 and 1991 both the gravel bars of the sedimentation zones and the intervening gravels declined in extent. For at least 100 years sedimentation zones dominated the river channel, being the focus of the majority of channel changes until their disappearance between 1951 and 1991.

Some key areas of further investigation are required to establish the causes of the observed changes in river channel behaviour. First the timing of sedimentation zone formation must be determined, which will require analysis of sources of planform information prior to 1856; the early plans described in chapter 3 could provide some of this evidence. Secondly, reconstructing the detail of actual channel planform changes will enable the significance of the results described to be evaluated in greater detail. This detail may also provide an indication of the nature and extent of local causes in channel behaviour to be identified. While catchment wide influences such as climate and metal mining were undoubtedly important, reach scale influences, such as gravel extraction, will also have been important. These should explain localised changes that appear to be contrary to changes elsewhere, for example the persistence of wide gravel bars in the lower catchment during 1951, and the anomalously high wetted width in sedimentation zone 5 during 1951. In addition, planform reconstruction will also allow the impact of flooding to be evaluated; for example, does this cause sedimentation zone formation, persistence or reduction? Planform reconstructions will enable the significance of bank erosion to be evaluated as this will reveal if channel widening is caused by bar formation or the lateral migration of the wetted channel. Determining the cause of the dramatic changes in channel widths between 1951 and 1991 will benefit from sources of planform information from additional years. A detailed chronology of channel change for the period immediately following the meridional climate phase (1955-1969) will enable the impact of this period to be investigated further.

Chapter 6

Reach-scale investigations into historic planform change.

6.1. Scope of chapter

The importance of large-scale controls on river channel planform were established by both the catchment-scale and trunk channel width series investigations. However the importance of local (reach specific) controls were not evaluated in these large and intermediate scale studies. Determining the extent to which local controls interact with catchment-scale forcing is a key issue in understanding the causes of river channel changes in upland catchments. The width series results emphasised differences in the timing and magnitude of channel changes, which may indicate the importance of such local controls. Reconstructing the actual changes in channel planform at selected sites enables the importance of local controls, such as those manifest in deviations from synchronous channel behaviour, to be established. The preceding results have emphasised that discrete reaches of extensive and persistent channel planform change could be identified throughout Weardale. These reaches appear to represent sections of river channel that are particularly sensitive to changes in flood frequency and magnitude and catchment land use. The responsive nature of such reaches makes them ideal for the reconstruction of river channel planform. A particular benefit of the reach scale approach is that additional archival sources that did not offer sufficient spatial coverage in the catchment-scale investigations can be integrated into the analysis. Of particular significance is the potential for early maps to better constrain the onset of sedimentation zone development.

In this chapter reach-scale channel planform reconstructions are presented for eight reaches in Weardale. The detail and potential cause of changes in channel planform are discussed, with particular attention being paid to the importance of reach specific influences. Channel planform change is quantified in each site through the measurement of gravel-bar area during each survey year. Finally the chapter considers the potential importance of individual reach-scale controls before considering how these may interact with catchment-scale influences.

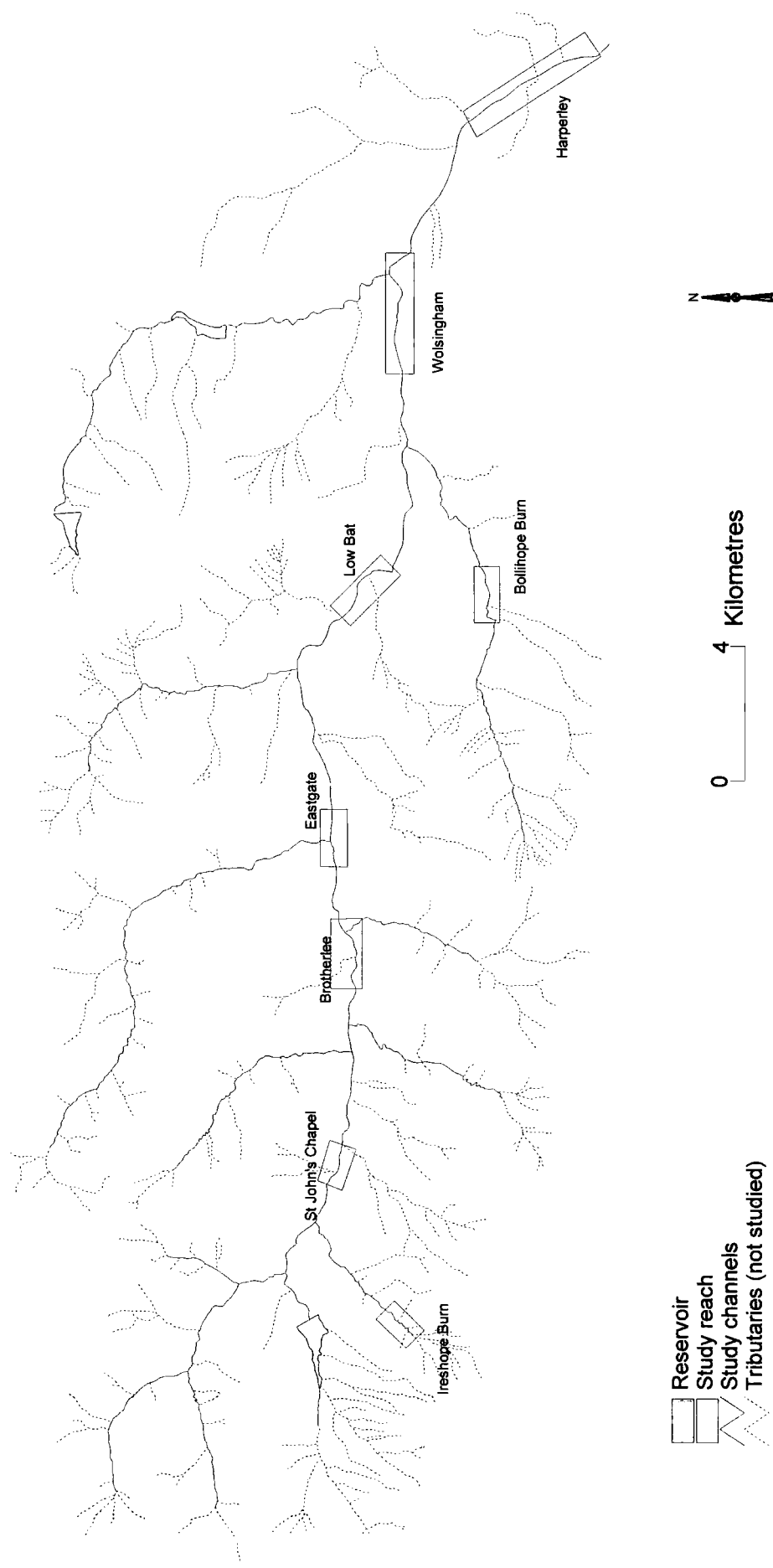
6.2 Study reach characteristics

Each of the eight reaches selected for detailed examination conforms well to the sedimentation zone characteristics of wandering gravel-bed rivers. These reaches are located widely through the catchment in both tributary and trunk channel settings (Figure 6.1). As well as providing an understanding of the importance of reach specific controls in a range of differing settings, the spatial distribution of these reaches offers the potential for catchment-scale events identified in the earlier chapters to be discerned. Determining the variation in the extent of gravel-bars in these sites over the historic period, for example, provides important calibration of the catchment scale analysis. These reaches are particularly well suited to an analysis of change as they have experienced changes in channel planform and gravel bar extents throughout the historic period. While the reaches can be broadly categorised as sedimentation zones, they each have their own specific characteristics (Table 6.1).

Table 6.1 Characteristics of Weardale study reaches.

Reach	Height (m O.D.)		Length (km)	Slope	Stream Order	Upstream catchment area (km ²)	Maximum width (m) (year)
	Upper	Lower					
Tributaries							
Ireshope Burn	450	400	0.890	0.056	4	3.8	40 (1856)
Bollihope Burn	250	230	1.320	0.015	4	27.7	53 (1856)
Trunk channel							
St John's Chapel	310	295	1.360	0.011	5	74	73 (1951)
Brotherlee	260	245	1.850	0.008	5	120	143 (1841)
Eastgate	233	219	2.480	0.006	5	162	144 (1856)
Low Bat	190	178	1.970	0.006	5	213	147 (1856)
Wolsingham	150	130	3.350	0.006	5	308	181 (1896)
Harperley	115	100	3.390	0.004	5	346	170 (1856)

Figure 6.1 Map showing the location of study reaches.



6.3 Historic planform changes along the sedimentation zones.

6.3.1. Ireshope Burn

In 1856 the Ireshope Burn study reach was characterised by extensive lateral bars, and large mid-channel bars, typically wider than two channel widths (Figure 6.2 and 6.3). This suggests relatively active rates of coarse sediment supply. An increase in the incidence of flooding has been cited as a possible cause of increased sediment supply to upland tributary streams (Merrett and Macklin, 1998). The historical flood record (Figure 4.14) indicates five large flood events affected the Wear catchment during the mid-nineteenth century. These floods may have initiated an increase in sediment delivery to the channel through erosion of surrounding tributary channels. Metal mining was also carried out along Ireshope Burn during the eighteenth and nineteenth centuries. Mining in the Ireshope catchment involved hushing, with several hushes cut into the valley sides (Figure 4.9). The 1991 aerial photograph indicates that these were well connected to the channel network and therefore may have delivered sediment directly to the river channel (Figure 6.4). The aerial photograph also demonstrates that many of the tributaries connected to the study reaches are incised, although their sides are now vegetated. It is likely that the extensive gravel bars were produced by a combination of flooding and mining activities.

A considerable reduction in the number and extent of active gravel bars occurred between 1856 and 1896 (Figure 6.3a). Channel changes over this period were associated with loss of lateral gravel bars (Figure 6.2 and 6.3) through vegetation colonisation, and where the channel formerly divided, the abandonment of secondary channels. Despite the relatively high flood frequency and magnitudes at this time (Figure 4.8) and continued metal mining in the catchment a decline in sediment supply appears to have occurred. The only significant change at this time appears to have been the cessation of hushing. Hushing in the North Pennines was carried out during the eighteenth century and declined during the early nineteenth century, although some hushes remained in use until the 1840s (Cranstone, 1992). The cessation of hushing was coincident with the decline in sediment delivery to the reach which suggests hushing may have been the principle cause of sedimentation along the reach. Channel planform transformation coincident with hushing has

Figure 6.2. Channel planform changes along the Ireshope Burn reach 1856-1991. Letters indicate locations referred to in the text. Flow is from bottom to top.

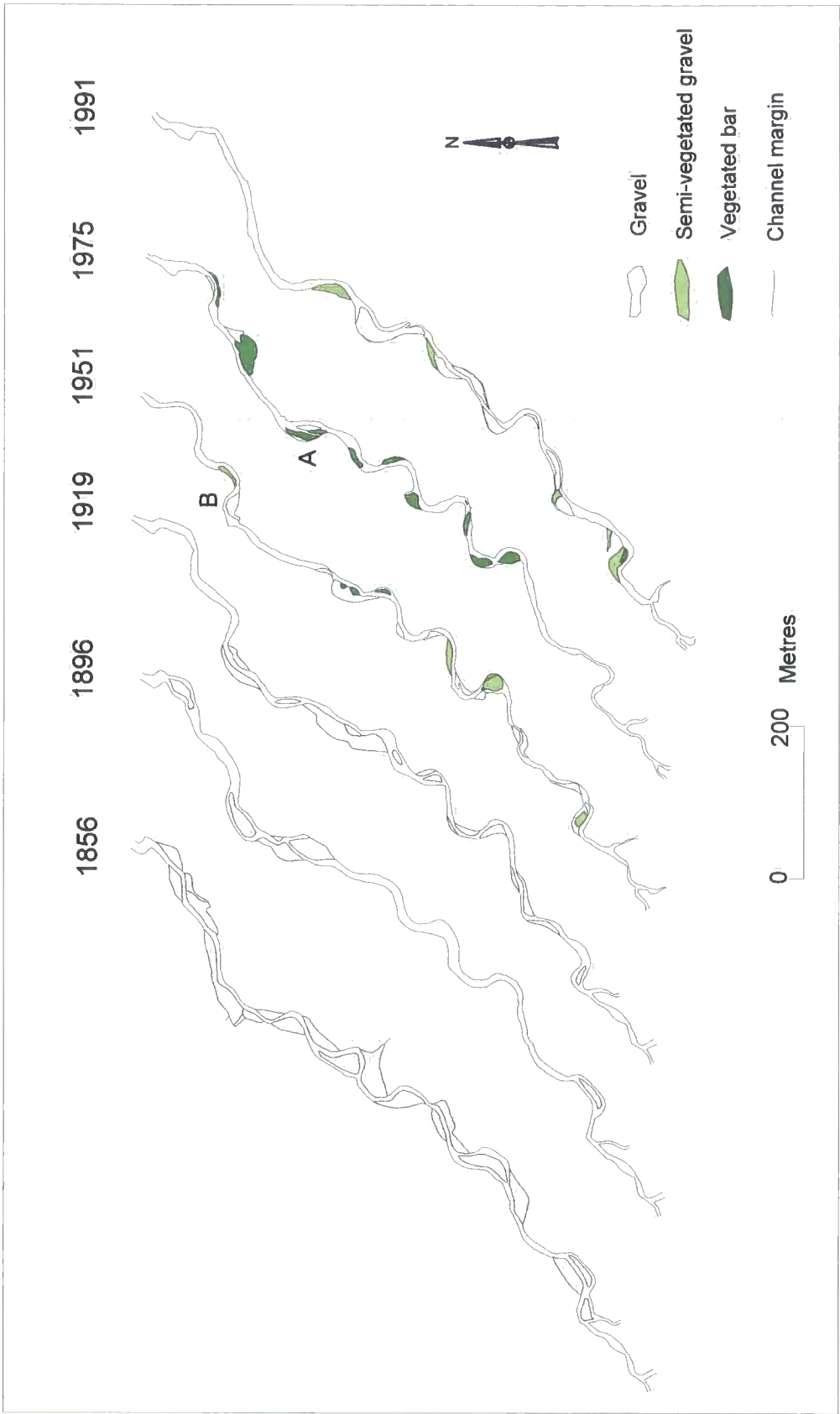


Figure 6.3. Change in bar area along the Ireshope Burn reach 1856-1991
 Note differing y-axis for mid-channel bars.

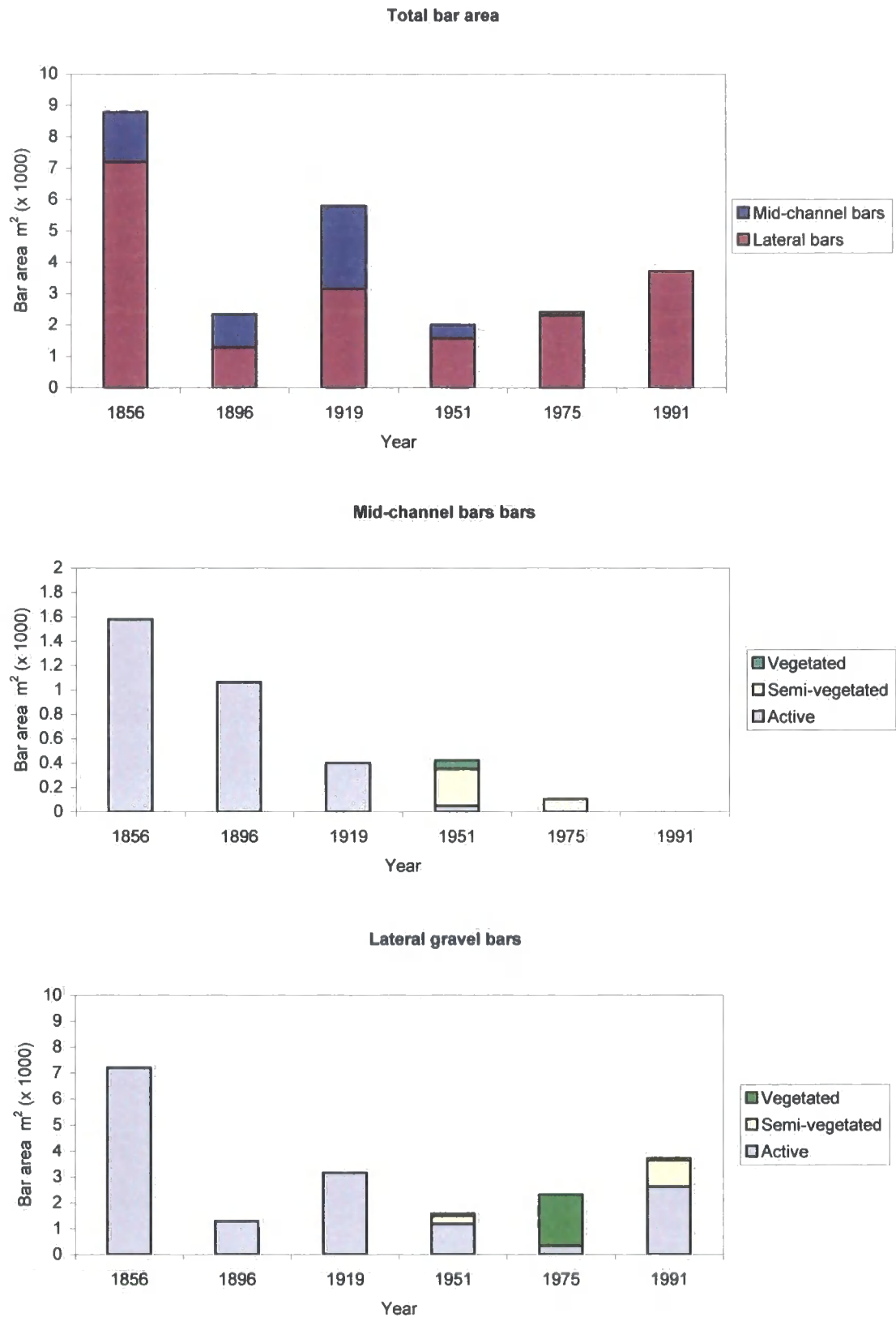
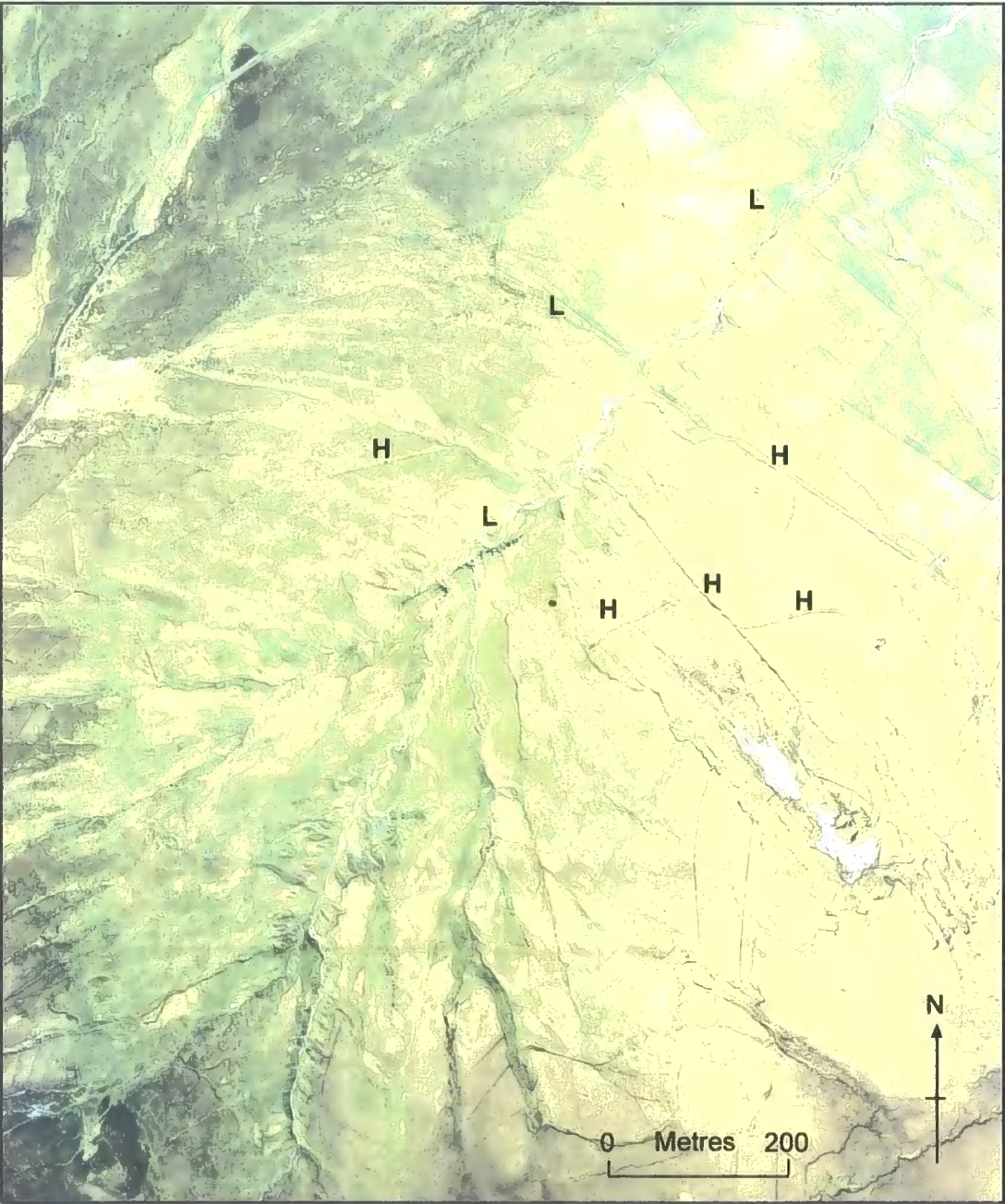


Figure 6.4. Aerial photograph of the Ireshope Burn reach.
Locations of hushes (H) and levels (L) are indicated. Note the peat slide to the south
east of the channel
Source: Aerofilms Ltd.



also been reported from parts of the South Tyne catchment (Macklin, 1997a).

Over the period 1896-1919 both the number and extent of gravel bars appears to have increased, including the formation of four new mid-channel bars (Figure 6.3), indicating renewed sedimentation in the reach at this time. This however, was at a time of low flood frequency and magnitude and was coincident with the decline of the metal mining industry. The relatively small size of the gravel bars in 1919 indicates sediment delivery was not as great as in 1856. Two localised high magnitude storms, not recorded in catchment-scale discharge histories (Figure 4.8), occurred during the early twentieth century. Documentary evidence indicates that a severe storm affected upper Weardale on October 6 1900, described by the rainfall observer at Eastgate (All Saints' Vicarage) as "Very wild and wet; the greatest flood on the Wear for many years" (Law et al., 1998). Another severe storm was reported on October 8 1903 which caused extensive flooding throughout northern England. Floods generated by these severe storms may have been responsible for the changes in channel morphology (cf. Carling, 1983a).

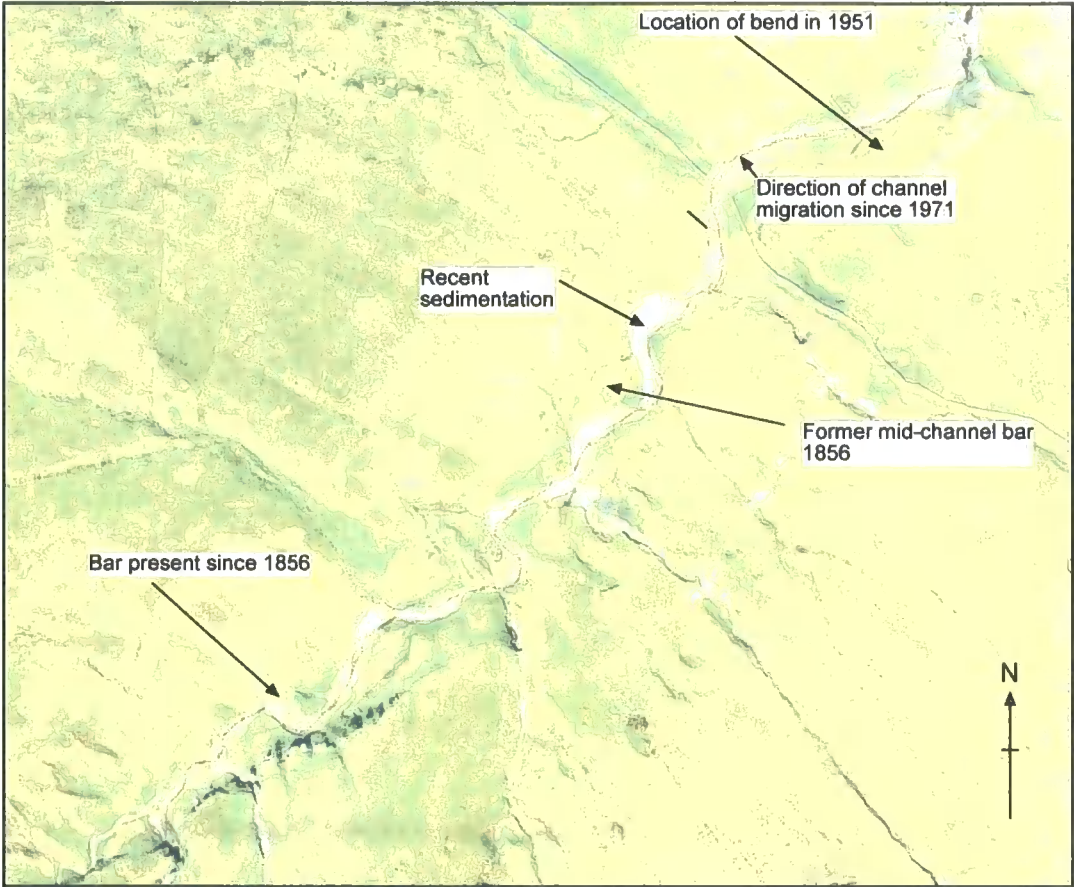
The general channel planform remained unchanged between 1919 and 1951 (Figure 6.2), and bar changes were restricted to re-organisation accompanied by a reduction in their extent (Figure 6.3a). This indicates that sediment delivery was low and that gravel re-working during high flow events was limited. This period corresponded to a phase of low flood frequency in the Wear catchment (Figure 4.14). Vegetation colonisation continued between 1951 and 1975 with the majority of formerly active bars becoming vegetated (Figure 6.2 and 6.3). Significant planform change occurred in locations A and B (Figure 6.2). Here two bends of the river were removed and the channel routed centrally between the former bends. The lower of the bends was occupied by vegetating gravel, suggesting the cut-off was coincident with sediment deposition. The slight increase in the extent of bars over this time period (Figure 6.3a) appears to be accounted for by sedimentation that was subsequently colonised by vegetation. Such changes are indicative of the effects of flooding and suggest another storm event occurred in the catchment between 1951 and 1975. The subsequent vegetation colonisation of gravel bars suggests this flood event occurred toward the beginning of this period.

A significant increase in the extent of active gravel bars occurred between 1975 and 1991 (Figure 6.2 and 6.3). Channel change both through the development of new active bars (Figure 6.3) and the re-routing of the channel thalweg also occurred,

although no mid-channel bars formed (Figure 6.2). Sedimentation within the channel resulted in the bypassing of several bends. A major storm occurred in the catchment on 17 July 1983 and was responsible for these changes (Figure 6.2). This flood has been particularly well documented (Archer, 1992; Carling, 1986a,b; Forbes, 1984). The flood was exceptional in its peak discharge and was capable of transporting large boulders (Archer, 1992). The transformation of the bars along the reach from a relatively stable state with limited active gravel to extensive active gravel bars appears to have been caused by this event. The significance of these low frequency high magnitude events is indicated by the relatively low flood frequency and magnitude experience in the Wear catchment at this time (Figure 4.8). The similarity in the nature of channel changes between 1896 and 1919, and 1975 to 1991 suggests the 1983 event may provide an analogy for the earlier events such as the storm of 6 October 1900. The sequence of planform changes indicated by the cartographic and aerial photograph sources described above is verified by the 1991 aerial photographs on which evidence of both recent and historic channel planform changes can be identified (Figure 6.5).

Channel changes associated with the flood in 1983 involved the infilling of former bends with fresh deposits and the re-working of lateral bar surfaces. This not only resulted in an increase in the extent of gravel bars (Figure 6.3a) but also resulted in localised re-routing of the wetted channel across the neck of former bends (Figure 6.5). Significantly, channel changes in the lower portion of the study reach between 1951 and 1975 show a similar pattern of bend abandonment which may also be the result of a flood event (Figure 6.2). The historical flood record (Figure 4.8) indicates that a large flood event occurred in the Wear catchment during 1968. Floods, particularly those associated with convective storms, can be important causes of increasing gravel bar extents in tributary catchments.

Figure 6.5. Areal photograph of the Ireshope Burn reach taken in 1991, showing the location of features identified in Figure 6.2. Flow is from bottom to top of the photograph.



6.3.2. *Bollihope Burn*

This study reach is located at the confluence with Howden Burn, where sedimentation is encouraged by low lateral confinement and a decline in valley slope. In 1856 the Bollihope Burn reach was characterised by large lateral gravel bars alternating between banks (Figure 6.6). In the upper section of the reach the channel was divided around a large vegetated island and several smaller active bars. The large area of these gravel bars may also reflect the combination of metal mining, a high degree of upstream slope channel coupling and flooding. Metal mining in the Bollihope catchment also consisted of the excavation of shafts, levels and hushes with three hushes being located in close proximity to the channel network. In addition, quarrying began along the south bank of the reach during the mid-nineteenth century.

The period 1856-1896 was characterised by a decline in the extent of active bars in the reach; the braid zone was abandoned and several lateral bars were lost (Figure 6.6). The isolation of these lateral bars was probably due to vegetation colonisation, similar to that recorded along Ireshope Burn during this period. Yet, metal mining in the catchment was at its most productive in the period 1868-1882 and quarrying along the south bank of the reach was extended at this time. The decline in the extent of active gravel between 1856 and 1919 may therefore have been related to the cessation of hushing during the mid-nineteenth century. Some bar re-organisation occurred during this period such as the formation of two new mid-channel bars, the largest of which appears to have formed in response to the installation of a weir across the channel. Weir construction was part of a river control scheme and the braid zone may also have been removed as part of these works. The motivation for conducting such changes is likely to have been related to quarrying activities; the weirs were constructed to encourage ponding to provide a water supply and channel realignment conducted to remove the threat from channel migration towards the quarry workings.

Following a phase of minor changes in channel planform between 1896 and 1919, significant planform change occurred between 1919 and 1951. The central and lower portions of the reach experienced a considerable increase in channel complexity, principally through the formation of mid-channel bars with lateral bars showing only a modest increase in extent (Figure 6.7). It is difficult to determine the exact cause of this sedimentation, as metal mining in the catchment had ceased and flood

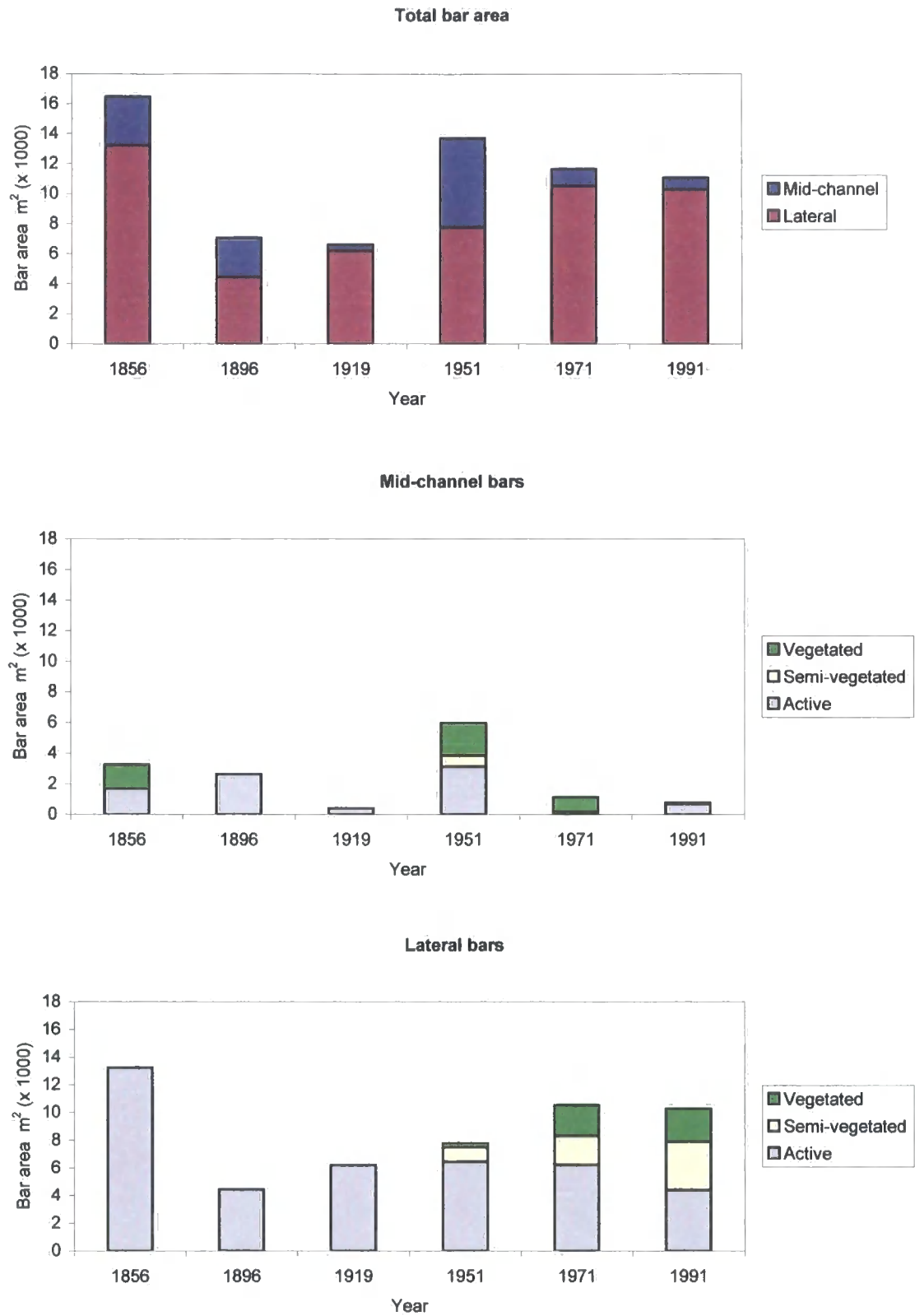
frequencies were low. Minor changes in gravel bars in the upstream portion of the reach and a decline in the extent of gravel around the tributary confluence suggest deposition was probably not associated with the delivery of sediment from upstream. Indeed, Ireshope Burn also experienced a decline in sedimentation at this time. Sedimentation is therefore likely to have been related to the quarrying operations along the reach.

Channel changes between 1951 and 1971 were also clustered in the central portion of the reach with only minor changes elsewhere. Overall the extent of gravel bars decreased, principally through a reduction in the extent of mid-channel bars, although lateral bars showed an increase in extent (Figure 6.7). The change in bar extents reflect the abandonment of the southern secondary channel (Figure 6.6) and vegetation colonisation, suggesting sediment delivery to the reach had declined substantially. This decline may have begun at some point prior to 1951 as indicated by the vegetation colonisation of the bars at this time (Figure 6.7). The decline in sedimentation appears to have been related to the decline of quarrying in this location. While the western third of the reach shows minor changes in bar distribution, the eastern third shows a substantial decline in the extent of both lateral and mid-channel bars. Between 1971 and 1991, with the exception of some local gravel re-working, the channel did not change significantly.

Figure 6.6 Channel planform changes along the Bollihope Burn reach 1856-1991. Flow is from left to right.



Figure 6.7 Change in bar area along the Bollihope Burn reach 1856-1991



6.3.3. *River Wear at St John's Chapel*

In 1856 the St John's Chapel reach was characterised by a single thread planform dominated by three large lateral bars located in the centre of the reach (Figure 6.8). The decline in the extent of lateral bars by 1896 (Figure 6.9) suggests sedimentation had decreased. However, by 1919 the extent of gravel bars had increased, becoming as extensive as during 1856. Sedimentation between 1856 and 1896 was particularly concentrated in location A; however, around 1919 the focus of sedimentation appears to have shifted upstream slightly to location B, where mid-channel bar development occurred. This suggests that a phase of sedimentation began during the early nineteenth century, before declining during the late nineteenth century. This may reflect a combination of metal mining (particularly hushing) in the surrounding tributaries (Figure 4.16c) and the flood events of the nineteenth century. The second phase of sedimentation between 1896 and 1919 corresponds to the re-working phase identified by the catchment scale analysis. The two large floods documented in upper Weardale during 1900 and 1903 may have been responsible for much of this re-working.

By 1951 the extent of gravel bars had increased substantially (Figure 6.9). The central left bank bar was partially vegetated although a dry distributary channel separated this from the floodplain. The increase in gravel-bar extent and development of the distributary channel is likely to have been caused by the flood of 1947. This was the largest flood recorded in the Wear since the late nineteenth century and followed a phase of low flood frequency and magnitude (Figure 4.8). The subsequent vegetation colonisation of these bars supports this conclusion as this rules out a phase of persistent renewed sedimentation.

Channel changes in the centre of the reach continued between 1951 and 1971. The large left bank bar was incorporated into the channel and mid-channel bar development along the reach peaked at this time (Figure 6.8). The significance of channel division declined substantially between 1971 and 1991, with only a residual mid-channel bar remaining in location B, which was reactivated. Much of the southern distributary channel was abandoned, as part of the former mid-channel bar became incorporated into the south bank. Vegetation colonisation removed the dry secondary channel in location B and the 1971 mid-channel bar became attached to the south bank.

Figure 6.8 Channel planform changes along the St John's Chapel reach 1856-1991. Letters indicate locations referred to in the text. Flow is from left to right.

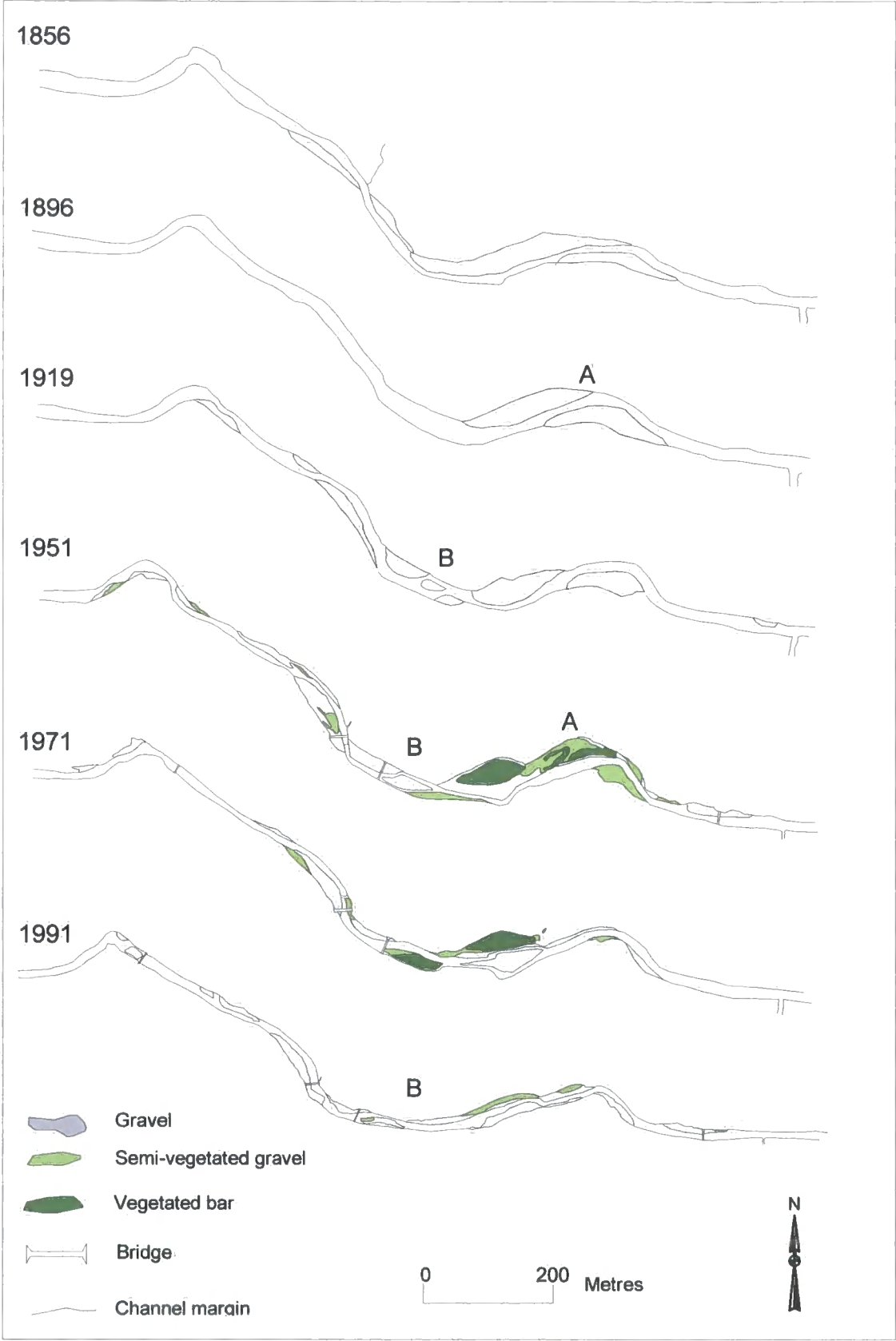
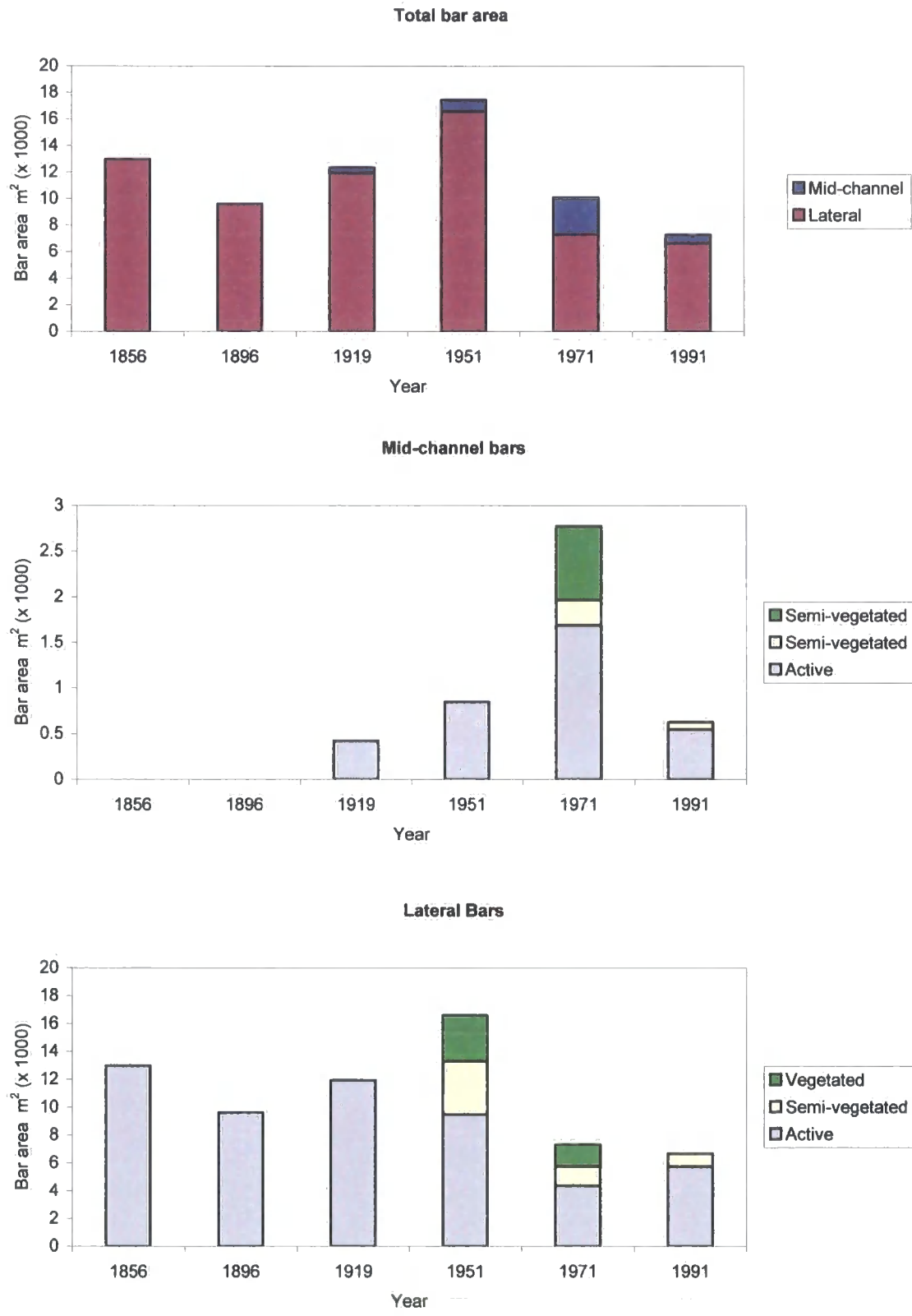


Figure 6.9. Change in bar area for the St John's reach 1856-1896
 Note differing y-axis for mid-channel bars.



Field investigations revealed that the mid-channel bar in location A is located on the front of a large riffle. This riffle is approximately 1 m in height, has a steep front and is the dominant bed form in the reach (Figure 6.10). This bar was more extensive in both 1951 and 1971, and appears to have receded particularly along the south bank where upstream incision has occurred (Figure 6.11). Coupled with vegetation colonisation of the bar surface this may represent the gradual re-adjustment of the reach following the 1947 flood, the emergent riffle representing the remains of a body of the sediment deposited by this flood. The steepness of the riffle front (Figure 6.11) suggests recent sedimentation in this reach and perhaps in response to the 1995 flood event (Figure 4.8).

Figure 6.10 View of the mid-channel bar in location A at the front of the emergent riffle structure.

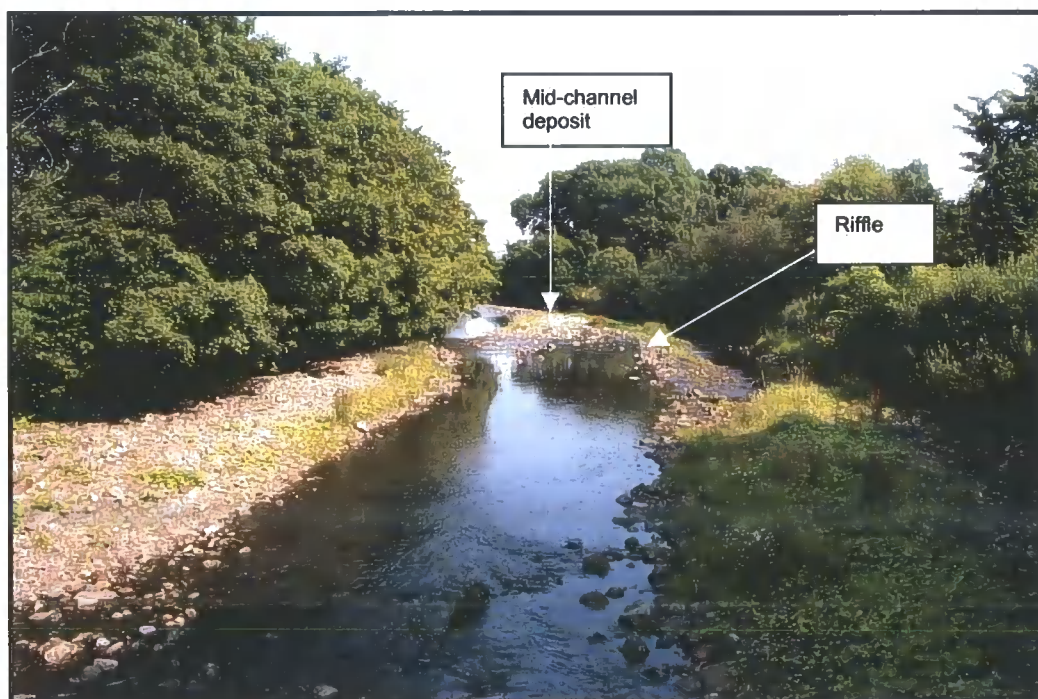


Figure 6.11 View looking upstream showing the fall in bed level across the riffle face and apparent bed lowering along the south bank.



6.3.4. *River Wear at Brotherlee*

The earliest available cartographic information for the River Wear at Brotherlee is provided by the tithe plan of 1841 (Figure 6.12). Although gravel bars were not depicted on this plan, by comparing the planform detail in the plan with the distribution of gravel bars in 1856 and aerial photography from 1991 (on which the location of former gravel bars can be discerned) (Figure 6.13), the gravel bar distribution could be reconstructed (Figure 6.14). Significantly the first edition Ordnance Survey map (1856) depicts two backwaters which represent the remains of the earlier secondary channels (1 and 2 on Figure 6.12). The planform reconstruction indicates that the channel in this location was braided during 1841 and was characterised by very extensive gravel bars (Figure 6.15). Channel braiding in this location may have been caused by a combination of relatively frequent large floods augmented by high sediment delivery from the tributary streams due to metal mining operations (Figure 4.16). Similar sedimentation in the trunk channel of the South Tyne during the late nineteenth century is thought to reflect a combination of flooding and metal mining (Macklin, 1997b; Macklin and Lewin, 1989; Passmore et al., 1993).

Figure 6.12 Channel planform changes along the Brotherlee reach 1844-1991. Letters and numbers indicate locations referred to in the text. Flow is from left to right.

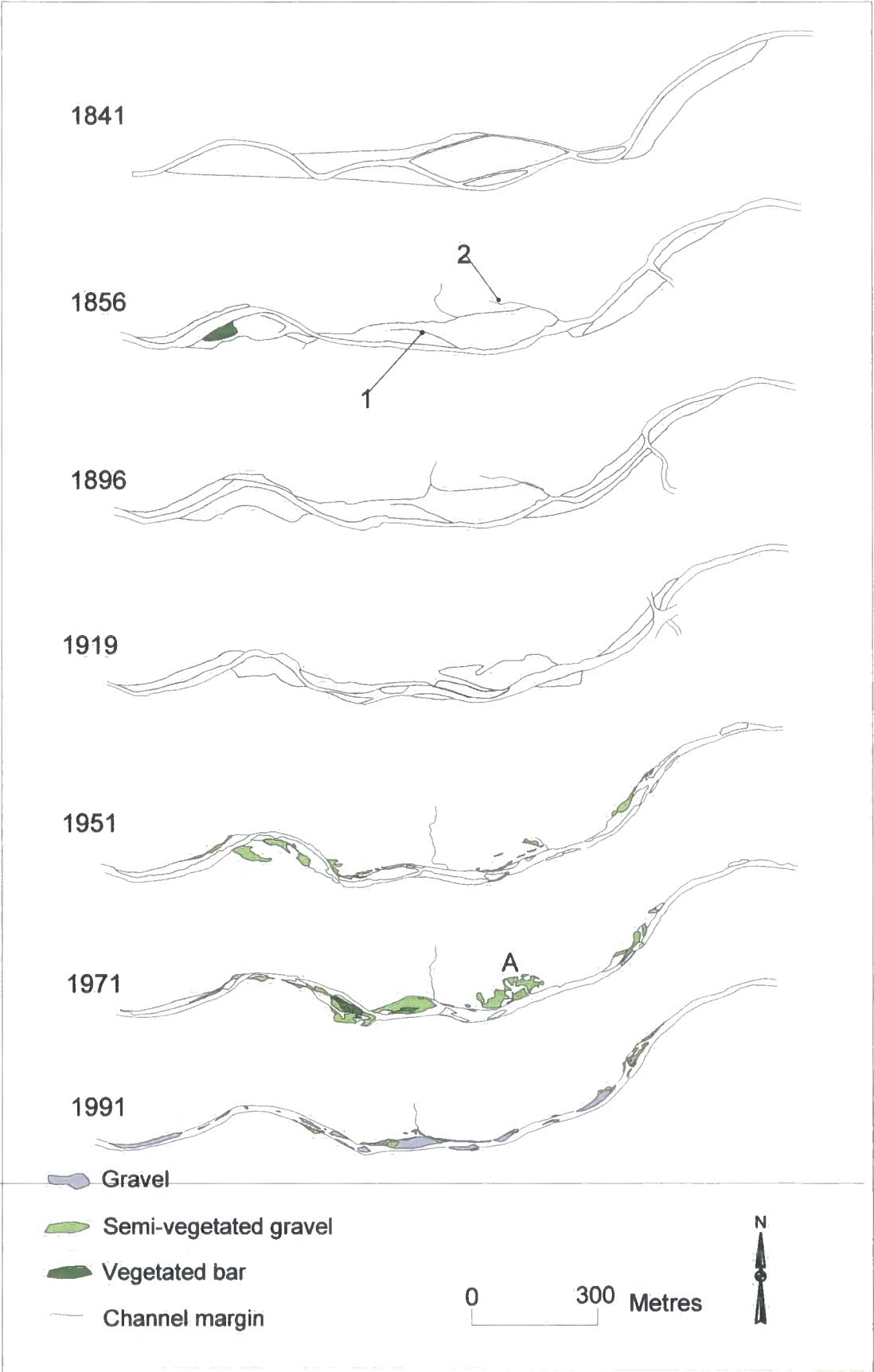


Figure 6.13 1991 aerial photograph of the Brotherlee reach. Flow is from left to right (Source Aerofilms Ltd).



Figure 6.14 Reconstruction of channel planform in the central portion of the Brotherlee reach, 1841.

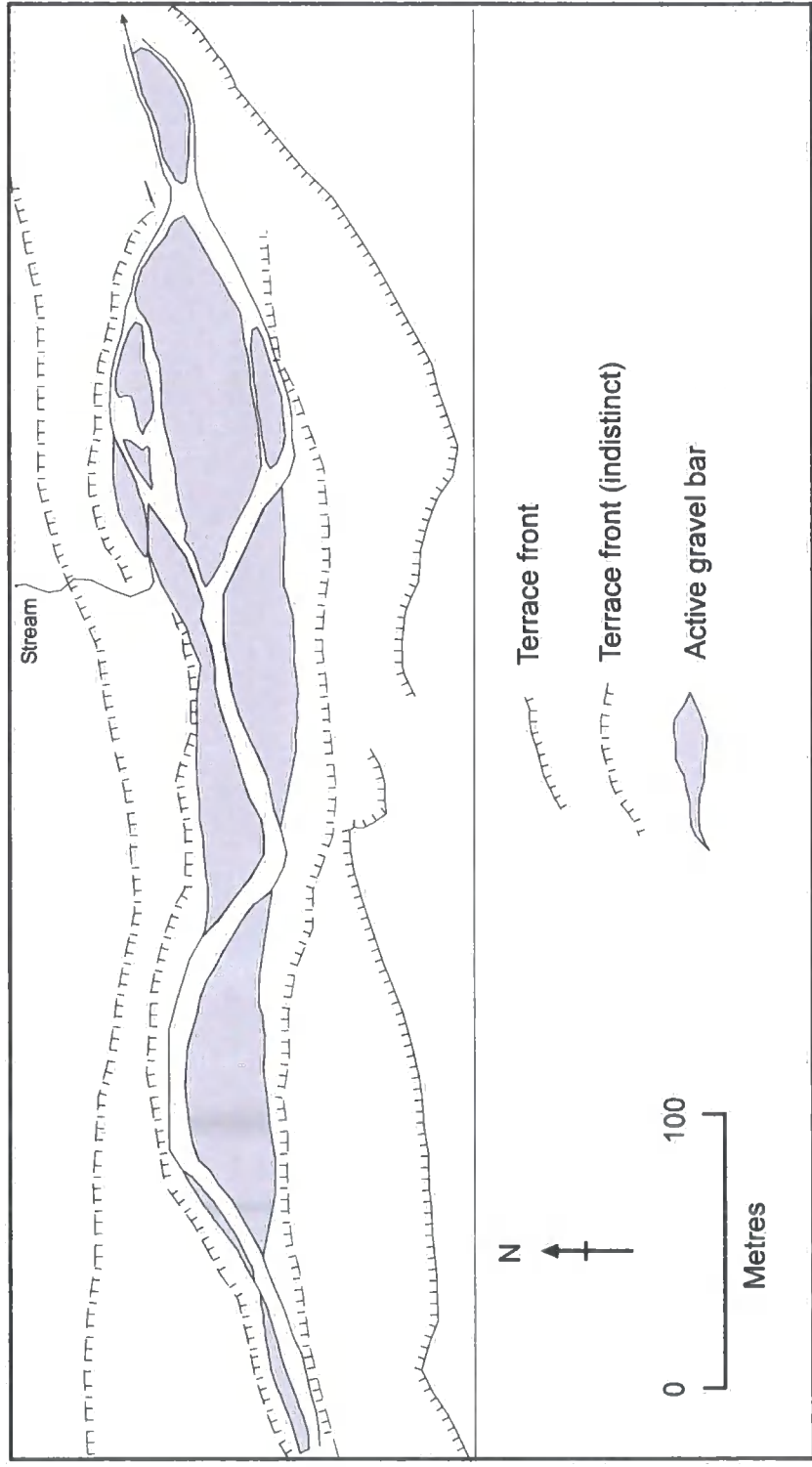
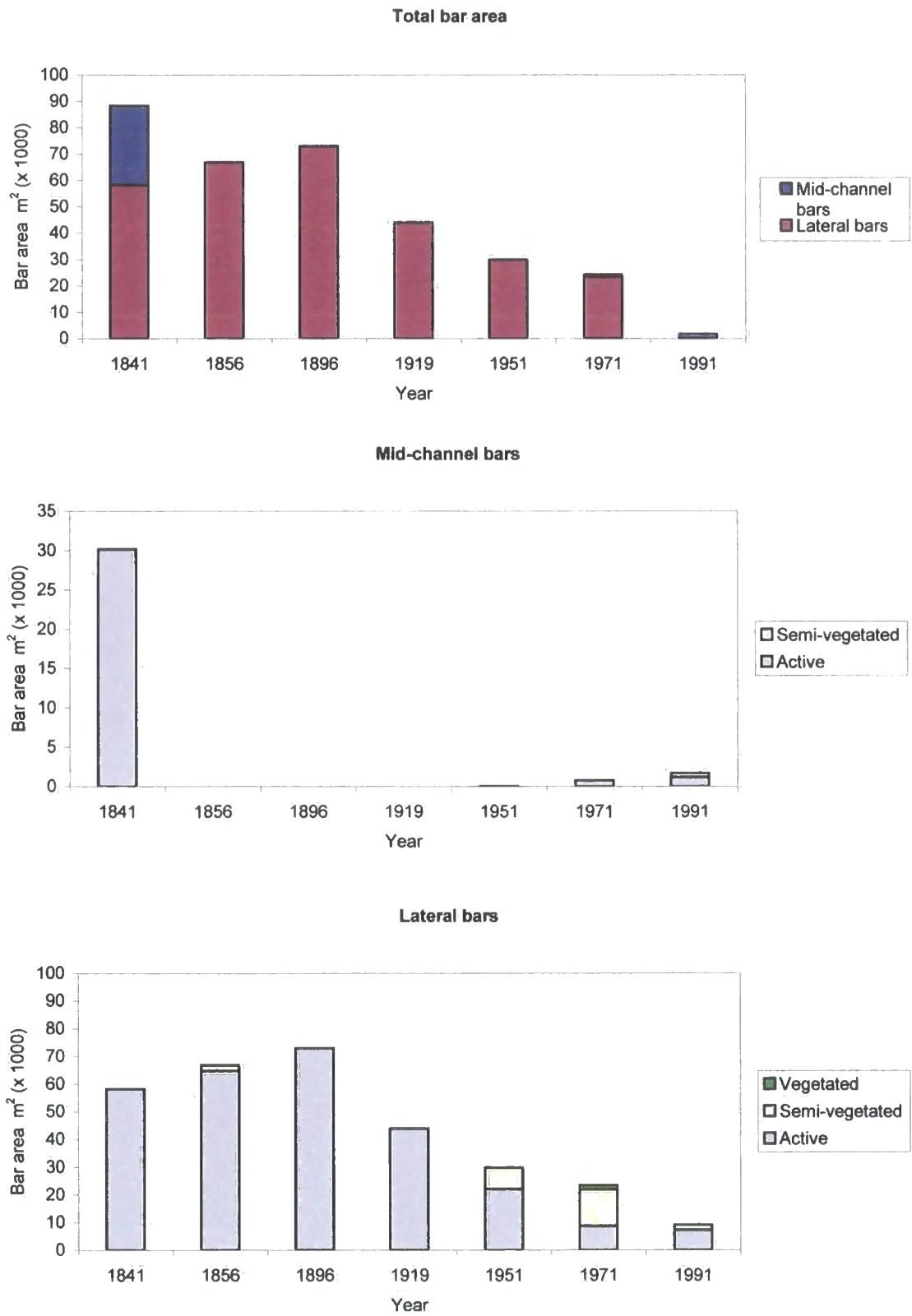


Figure 6.15. Change in bar area along the Brotherlee reach 1841-1991
Note differing y-axis for mid-channel bars.



By 1856 however, the channel had adopted a single thread planform, coincident with the rerouting of the channel thalweg in the central portion of the reach. The overall extent of gravel bars remains high, although only as lateral bars (Figure 6.15). Transformation of the channel from a divided planform to a single thread planform may have been encouraged by the passage of large floods in 1846 and 1853 (Figure 4.8). While earlier floods appear to have promoted channel division these subsequent floods appear to have filled in the distributary channel, a process recognised on the South Tyne (Passmore et al., 1993). The channel has adopted a straighter channel along the southern bank. Channel planform simplification following large floods has been reported in other braided channels in the UK (Hitchcock, 1977). In the case of the Brotherlee reach sedimentation during the mid-nineteenth century may have resulted in an increase in local channel gradient, which subsequently promoted channel incision. Erosive responses to channel aggradation such as this and slope increases have been reported in Scottish gravel-bed rivers (Richards, 2002).

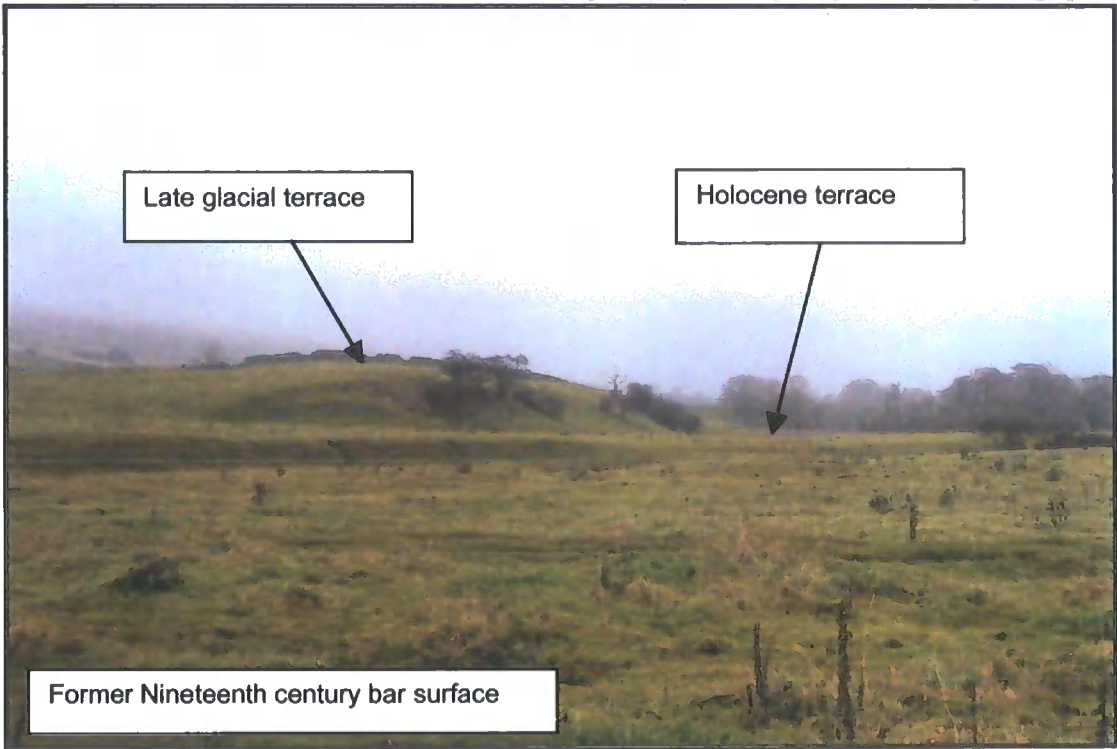
Gravel bar extent in the Brotherlee reach increased slightly between 1856 and 1896 (Figure 6.15). The maintenance of large lateral gravel bars in the central portion of the reach between 1856 and 1896, despite the diversion of the wetted channel, suggests metal contamination prevented vegetation colonisation, particularly as metal mining in the catchment reached its peak at this time. In addition, flood frequency and magnitude remained relatively high with floods capable of re-working the lateral bars maintaining the extent of active gravel. A particularly large flood passed through Weardale during 1881 (Egglestone, 1881).

The extent of gravel bars had declined substantially by 1919 (Figure 6.15) through vegetation colonisation (Figure 6.12). The decline in metal mining and flood frequency and magnitude between 1896 and 1919 enabled vegetation colonisation of the lateral bars as mining contamination declined and the inundation of bar surfaces declined. Three small bars developed in the centre of the reach (Figure 6.12) and appear to have been distinct from the larger bars as they were located within the active channel. These bars indicate re-working within the reach, perhaps during two large floods documented in Weardale during in 1900 and 1903 (Archer, 1992).

Channel changes subsequent to 1919 were dominated by a decline in the extent of gravel bars and although the extent of mid-channel bars increased these remained relatively insignificant compared to lateral bars. Increases in the extent of partially

vegetated gravel in location A, between 1951 and 1971 (Figure 6.12), corresponds to small scale gravel extraction from the bar during 1968 (Moore, 1994) and following the cessation of extraction vegetation colonisation occurred. The completeness of vegetation colonisation of the nineteenth century bars is illustrated by Figure 6.16, which views the northern portion of the large left bank bar (1856-1919).

Figure 6.16 Photograph showing the former large nineteenth century gravel bar surface on the north side of the River Wear at Brotherlee.



6.3.5. *River Wear at Eastgate*

The Eastgate reach showed a similar trend in declining gravel extent to that recorded along the Brotherlee reach. This is perhaps unsurprising given the proximity of these reaches. The channel planform in 1857 was dominated by frequent large lateral bars and occasional mid-channel bars (Figure 6.17), although mid-channel bars contributed a minor component of the total bar area (Figure 6.18). The extensive active gravel at the confluence of the south bank tributary appears to represent sediment delivery during the early nineteenth century. Given the relatively limited catchment area of this tributary, the sedimentation appears to represent a major disturbance in its catchment. The operation of four metal mines in this catchment during the nineteenth century (Figure 4.9) may account for the high sediment yield from this catchment at this time. The backwater in the centre of the reach represents an abandoned bend. The presence of short watercourses draining into this water body indicates that abandonment was relatively recent. However this bend was not active in 1844 (Tithe plan evidence) suggesting abandonment occurred earlier in the nineteenth century. The shape of the bar at location A and the area of vegetated gravel suggests that flow may have formerly been routed along the north bank, forming a bend similar to the abandoned bend upstream. This bend was abandoned by the diversion of flow across the neck leaving the former bend core remaining as a vegetated mound. The synchrony of response between this reach and Brotherlee (Figure 6.15) suggests that catchment-scale influences such as metal mining and flooding were the principal control on channel planform, particularly the extent of active gravel.

Between 1857 and 1896 a slight increase in gravel area occurred through an increase in lateral bar area (Figure 6.18). The bend in the upper third of the reach was bypassed becoming filled with gravel. This change was coincident with the construction of a railway bridge in this location. The bend may have been deliberately engineered to direct flow under the new bridge and prevent erosion of the outer bank of the bend that could undermined the new railway. However this change could also have been induced by the flood of 1881 (Egglestone, 1881) and changes elsewhere in the reach appear to represent the impact of a flood. For example, the spread of sediment deposited on the north bank of the channel in the centre of the reach indicates recent out-of-channel flow of sufficient magnitude to deposit coarse sediment (Figure 6.17). The location of this sedimentation was coincident with the abandoned channel present in 1857. The angle of the channel

Figure 6.17. Channel planform changes along the Eastgate reach 1857-1991. Letters indicate locations referred to in the text. Flow is from left to right.

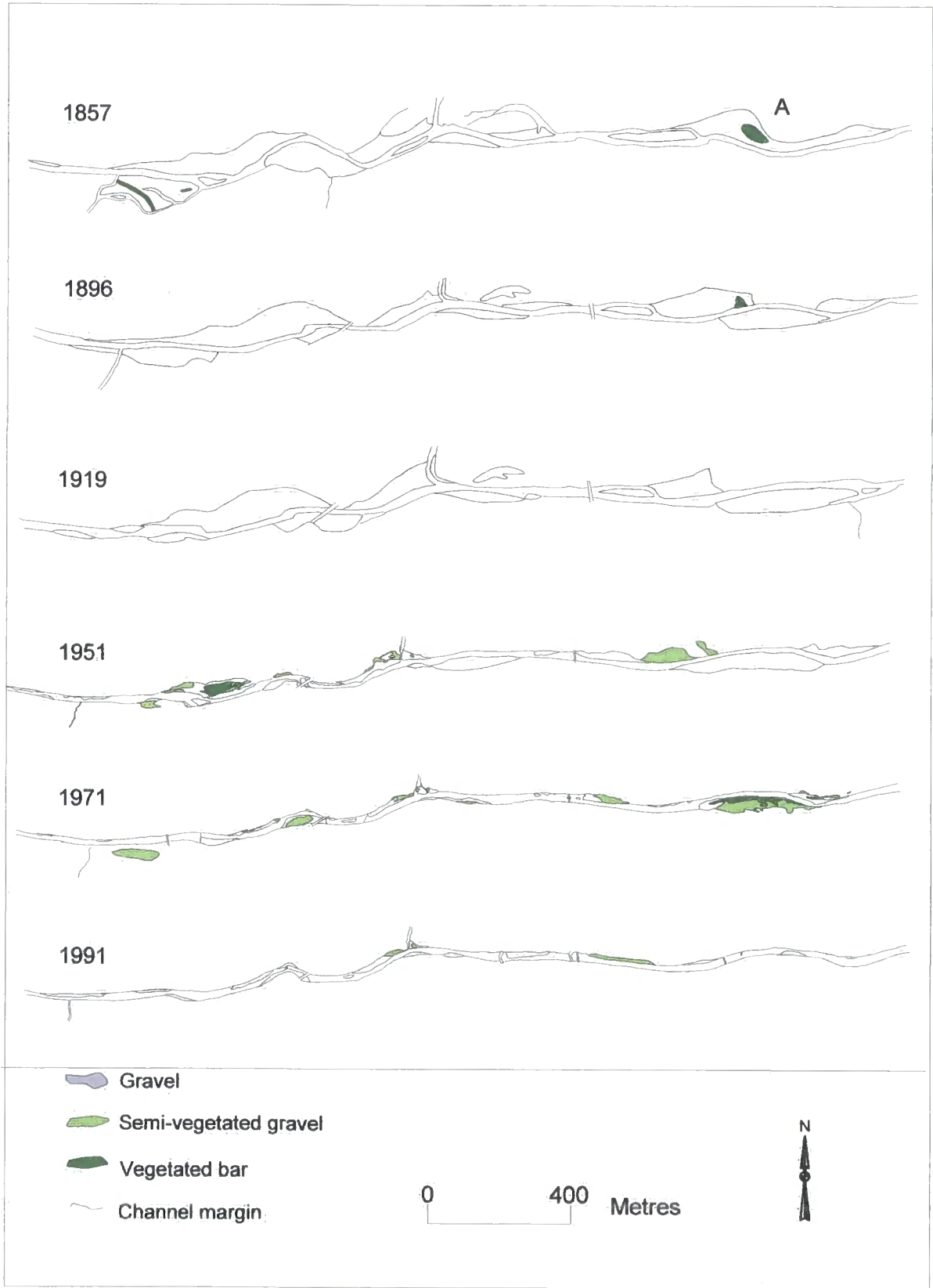
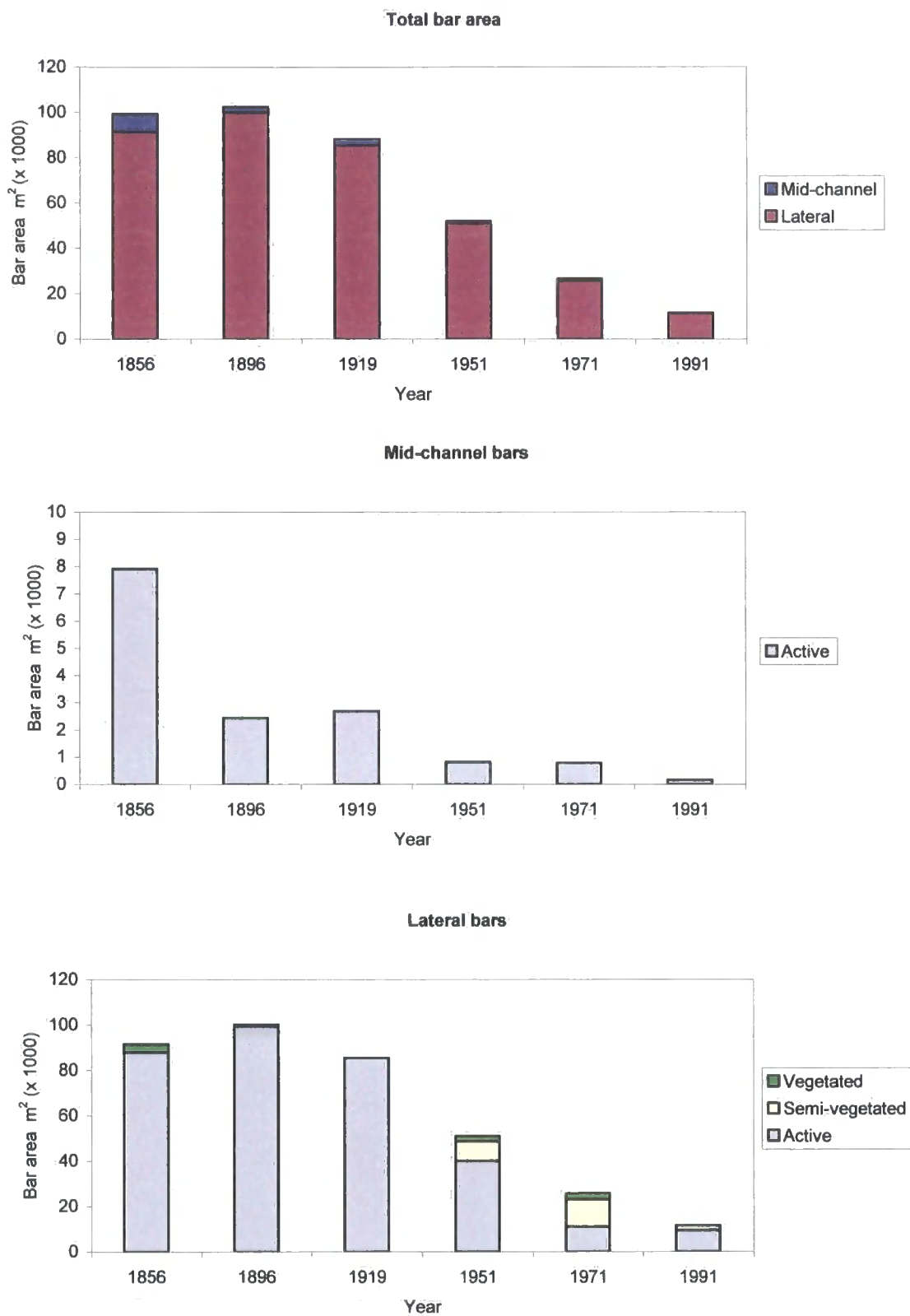


Figure 6.18. Change in bar area along the Eastgate reach 1856-1991
Note differing y-axis for mid-channel bars.



approach, the relatively low elevation of the bank in this location, and the palaeochannel forming a depression, would have encouraged the deposition of sediment in this location during a flood. Additionally, in location A the channel migrated laterally, removing part of the vegetated bar and forming a new lateral bar on the southern bank. This flood may also account for the slight increase in the extent of active gravel between 1857 and 1896.

In the years following 1896 the extent of active gravel along the reach declined progressively. Only minor planform changes occurred between 1896 and 1919 (Figure 6.17) in association with a slight decline in gravel bar area and this decline continued in the subsequent years (Figure 6.18). The overall channel routing along this reach remained unchanged from 1919 onwards. This was likely to be a response to decreasing flood frequency and magnitude, and metal mining which also declined at this time. The relatively slow decline in the extent of lateral bars between 1896 and 1951 suggests vegetation colonisation was still hampered by heavy metal pollution.

6.3.6. River Wear at Low Bat

Two extensive lateral bars and four large mid-channel bars dominated the Low Bat reach in 1856 (Figure 6.19). The presence of large lateral bars in locations A and B in 1856 with local vegetation colonisation suggests that sedimentation in the reach began during the early nineteenth century. This complements the evidence from both Brotherlee and Eastgate. Many of these lateral bars had apparently become separate from those located within the active channel. The loss of these bars by 1896, while adjoining bars remained present suggests they were located at a higher level than the active gravel proximal to the channel, being relics of a phase of higher sedimentation. Elsewhere in the reach channel changes were principally associated with the re-organisation of mid-channel bars. The changes between 1856 and 1896 were dominated by the decline in lateral bar extent, while mid-channel bars showed a slight decrease (Figure 6.20).

Channel changes between 1896 and 1919 also involved the movement of gravel within the reach, with total bar area showing a slight decrease (Figure 6.20). Between 1919 and 1951 the reach experienced a slight increase in the extent of gravel bars (Figure 6.20), the nature of which suggests a phase of renewed sedimentation. In location C, sedimentation occurred resulting in channel widening by erosion of the right bank which would have contributed further sediment to the channel. In location D the mid-channel bar increased in size. While the centre of the bar (active in 1919) became vegetated, bar growth occurred through the accretion of sediment on the upstream and right flank of the bar (Figure 6.19).

At some point between 1951 and 1971 the channel planform became almost entirely single thread, with mid-channel bars declining substantially (Figure 6.20). In both locations C and D, a new channel alignment was formed through the locations of bars present in 1951. Weirs were also installed along the reach, particularly in location C. These channel realignments increased the significance of lateral bars along the reach and account for the increase in total bar extent (Figure 6.20). The overall channel planform remained unchanged between 1971 and 1991 along the reach. However vegetation colonisation, which was beginning in a number of locations during 1971 led to a substantial reduction in the number of lateral bars. By 1991 the reach was characterised by a single-thread planform with occasional small lateral bars.

Figure 6.19 Channel planform changes along the Low Bat reach 1856-1991. Letters indicate channel locations referred to in text. Flow is from top to bottom.

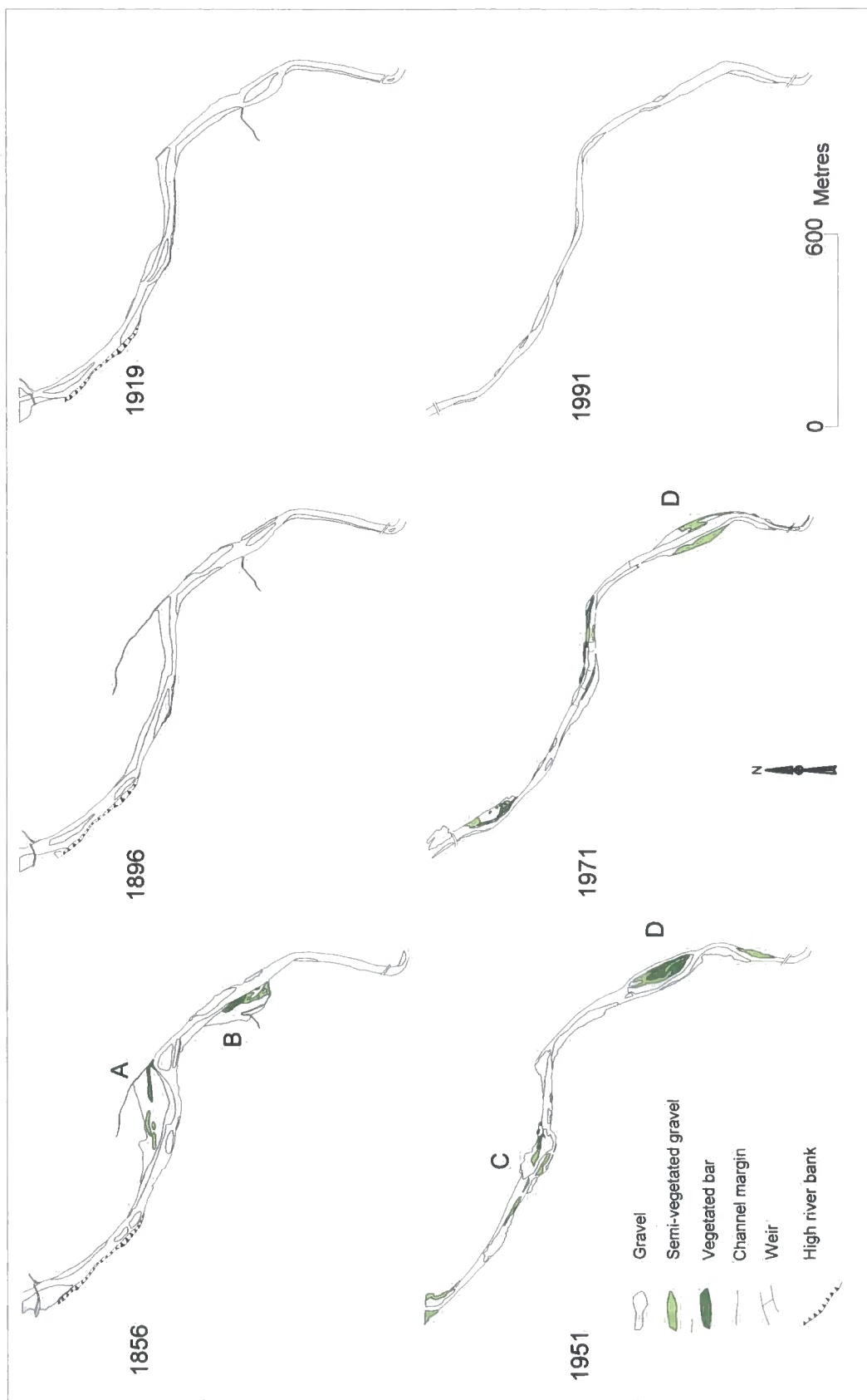
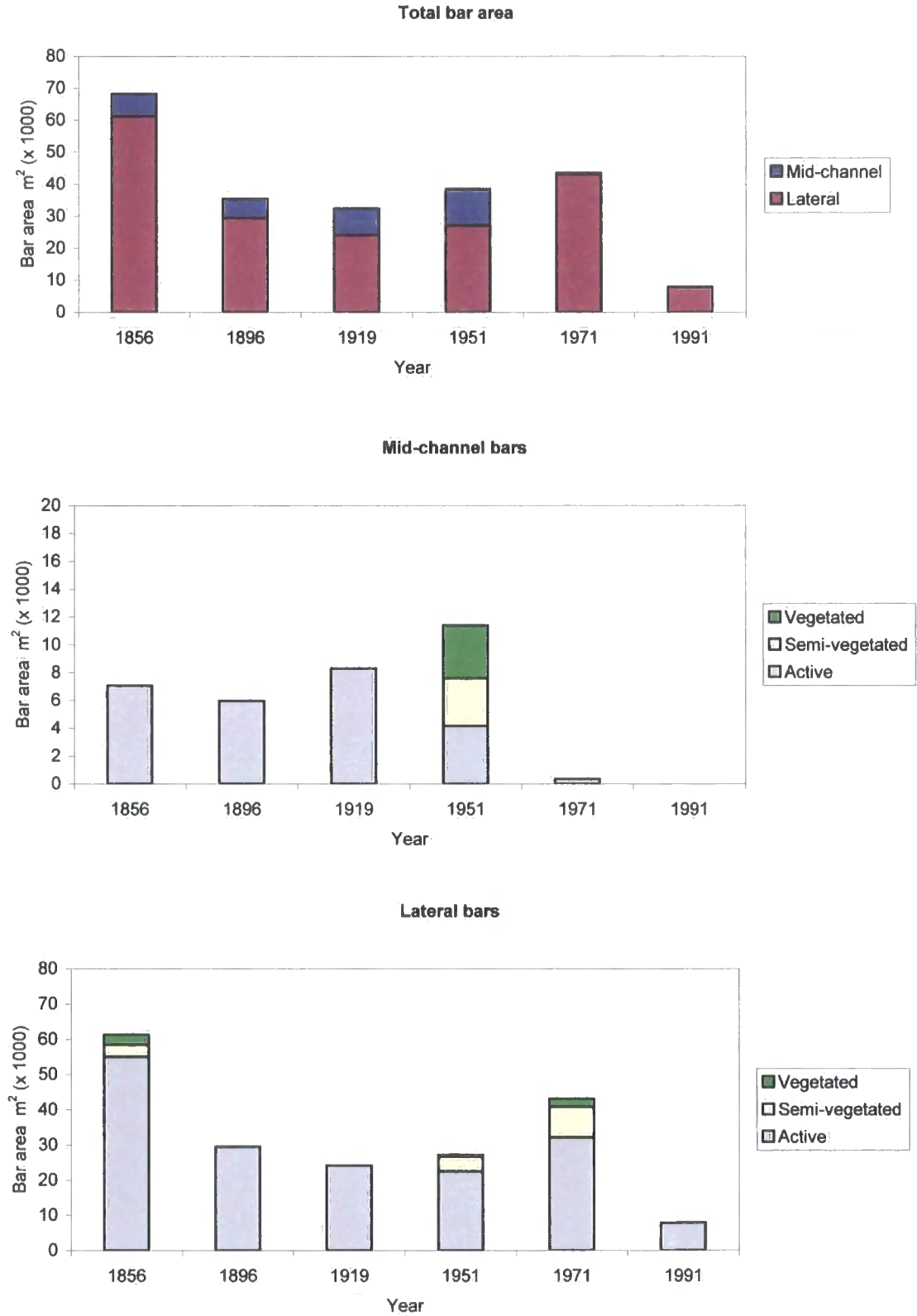


Figure 6.20 Change in bar area along the Low Bat reach 1856-1896
 Note differing y-axis for mid-channel bars.



6.3.7. River Wear at Wolsingham

In 1844 the Wolsingham reach was characterised by a single thread channel with lateral gravel bars, with the exception of a small mid-channel bar at the eastern bend of the reach. This is supported by evidence on the tithe plan, which indicates that the channel was largely single thread during 1839 (Figure 6.21). The narrow secondary channel in the central portion of the reach during 1844 is a millrace (Figure 6.22). The period between 1844 and 1858 showed a significant increase in gravel bar area coincident with channel widening and division in the central portion of the reach (Figure 6.23). However, the mid-channel bar on the eastern bend became attached to the left bank. This phase of sedimentation occurred later than increases upstream (Brotherlee, Eastgate and Low Bat) and suggests the channel was responding to the downstream transfer of sediment delivered from the tributary channels. Flooding during the early nineteenth century (Figure 4.6) will have promoted the transfer of sediment. The deposition of heavy-metal-contaminated fine sediment is likely to have contributed to these changes by destabilising the river channel, increasing its sensitivity to flooding.

Figure 6.21 Comparison of the river channel at Wolsingham as depicted on the tithe plan and railway plans. Flow is from left to right.

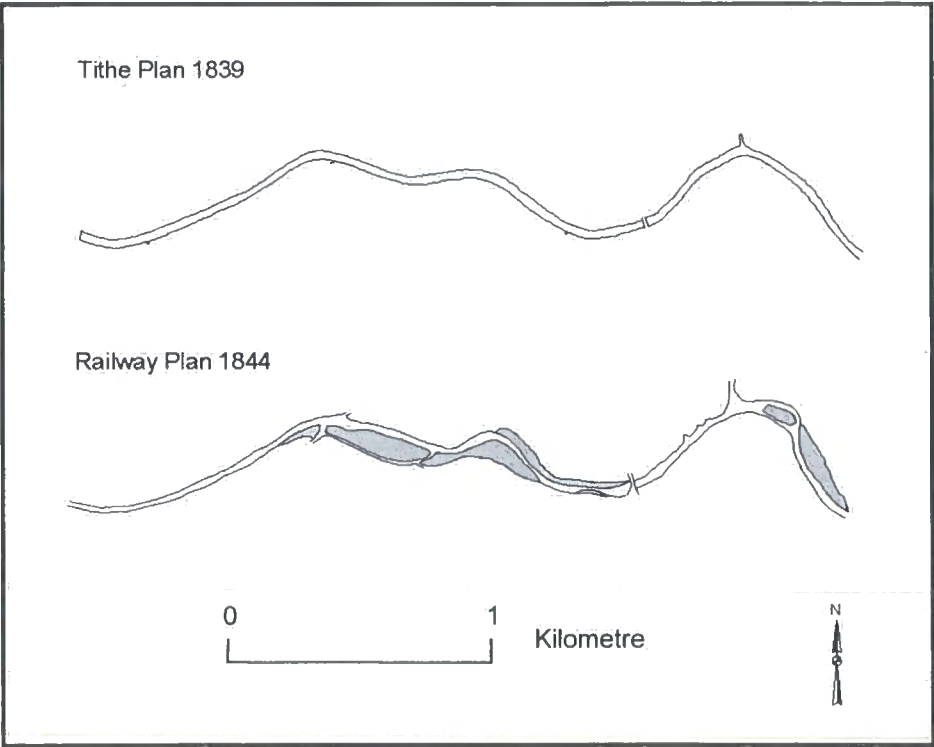


Figure 6.22. Channel planform changes along the Wolsigham reach 1844-1991. Letters indicate locations referred to in the text. MR = Mill race. Flow is from left to right.

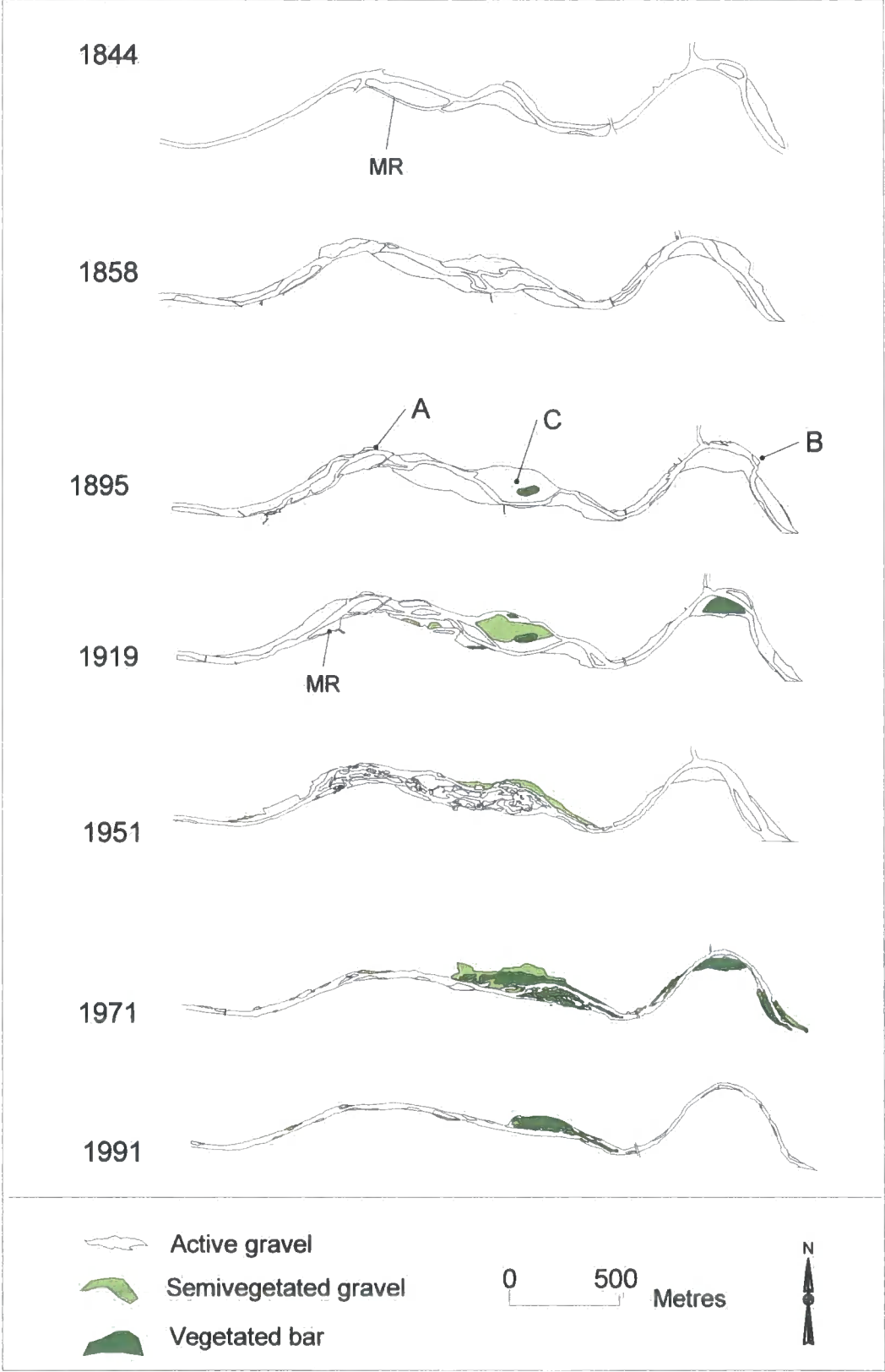
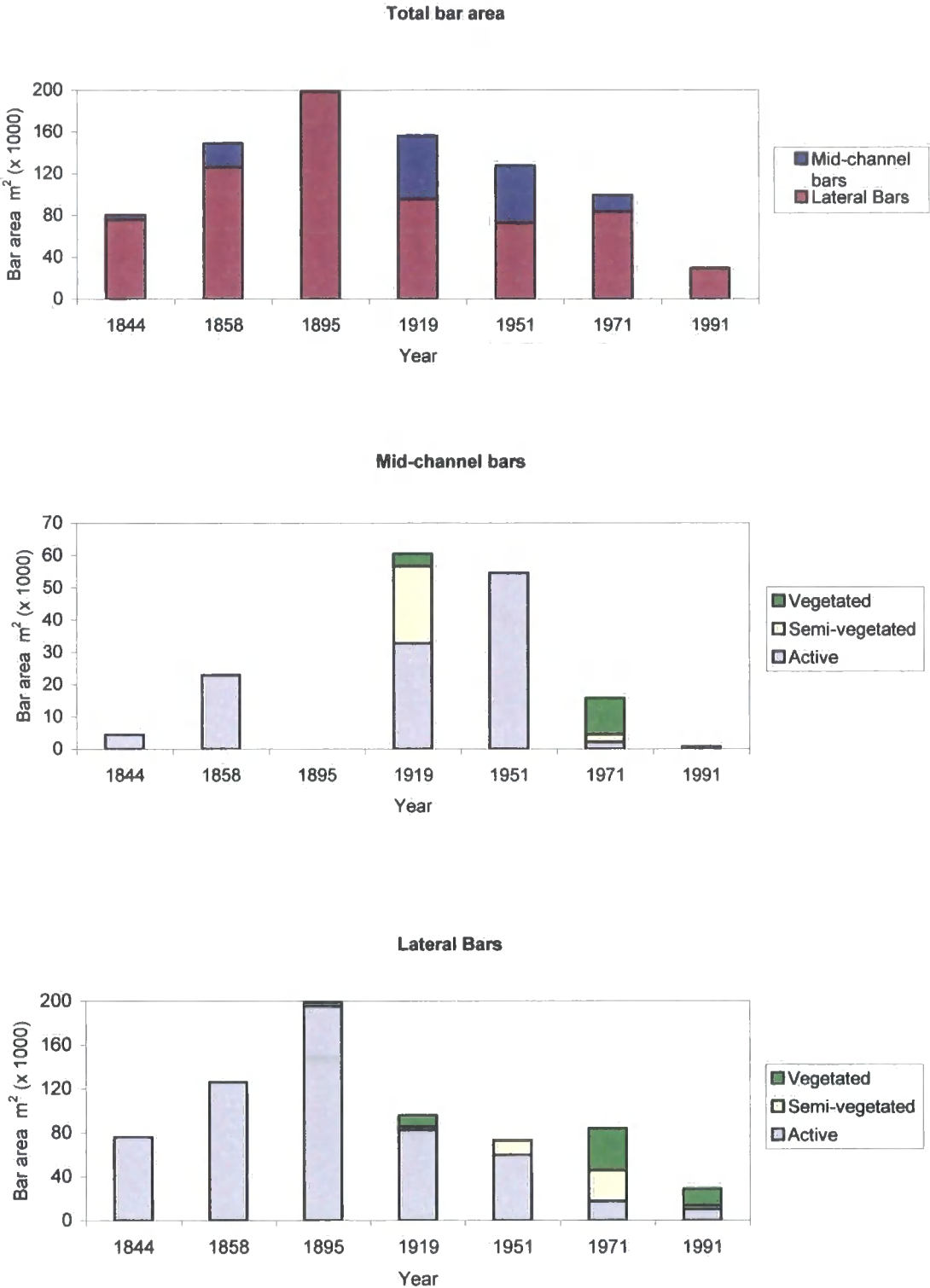


Figure 6.23 Change in bar area along the Wolsingham reach 1956-1991
 Note differing y-axis for mid-channel bars.



Active gravel area continued to increase at Wolsingham during the period between 1858 and 1895 (Figure 6.23). A particularly large flood is known to have occurred in Weardale during 1881. Descriptions of the impact of this flood on the river channel from the time correspond well to the changes recorded in map evidence:

"In the Wolsingham district where the river bed is wide and immense gravel beds exist, considerable damage was done. Immediately above the high dam [weir] the river entered the north bank and carried away part of the main road" (Egglesstone, 1881 p11).

This change is evident in location A on the 1895 map of Figure 6.22.

"Below Waskerley foot the stream rushed against the north side, carrying away a considerable quantity of the first and second fields, and about one hundred and thirty-three yards of the Wolsingham out-let sewer were destroyed, owing to the disappearance of this land.... The fields in some parts were covered with gravel, in others sand had accumulated, and field walls lay broadcast where the flood has swept" (Egglesstone, 1881 p11-12).

This change be seen clearly in location B of Figure 6.22, where bend and bar growth had occurred.

"The bed of the river in some places was considerably altered. above high dam near Wolsingham, the river bed was several feet higher, and in some places the Wear had made itself new channels" (Egglesstone, 1881 p11).

In location C (Figure 6.22) the channel thalweg has shifted towards the southern bank. Planform changes following flood events such as these are reported widely, as sediment is re-distributed within the channel belt leading to bar dissection and channel avulsion (Macklin, 1986a; Warburton et al., 2002). Frequent high magnitude flooding capable of re-working both the channel bed and exposed bars prevents vegetation colonisation. The channel planform continued to adjust during the early twentieth century; in 1919 the channel at Wolsingham exhibited extensive channel division (Figure 6.22 and 6.23) with flow dissecting a number of former lateral bars. However the marked reduction in both flood frequency and magnitude during the twentieth century was coincident with increased vegetation colonisation of the channel bars.

The gravel bar distribution in the central portion of the reach in 1951 showed a dramatic change, with numerous small active gravel bars present throughout (Figure 6.22). The bars which showed vegetation colonisation in 1919 had been destroyed and replaced by fragmentary gravel bars separated by numerous narrow channels. The area of active mid-channel bars increased, despite the total area of mid-channel bars remaining virtually unchanged since 1919 (Figure 6.23). These changes were produced by in-channel gravel extraction operations.

At Wolsingham gravel extraction averaging 36,000 tonnes per year commenced in the central portion of the reach in July 1945. Extraction, in the form of pit excavation, was initially focused on the bar in location C (Figure 6.22), however as operations progressed the entire channel bed in the central portion of the reach was worked with flow routing altered as necessary. Although an increase in gravel bar area would be expected, water filled pits and additional channels, produced during extraction, account for the decline in total exposed bar area between 1919 and 1951 (Figure 6.23). This accounts for the increase in wetted width detected in this location in chapter 5. The routing of the main channel was switched between left and right banks as each major channel was excavated. Durham County Council records from 1949 indicate that extraction lowered the bed of the northern channel, by as much as 2 m locally, which accelerated bank erosion causing pre-existing remediation structures to be undermined and collapse. By 1950 bed lowering had propagated 200 m upstream to a depth of approximately 0.3 m leading to the exposure of bridge foundations at Harelaw. Council records also indicate the release of suspended sediment during extraction and onsite gravel crushing, resulting in fish deaths and shoaling up to 10 km downstream.

Geomorphic adjustments along the reach prompted remediation work throughout the 1950s. Settling ponds were installed to trap fine sediment, although in practice these were rarely emptied and problems with fine sediment release continued throughout the life of the works. Bank protection work was carried out locally, in the form of gabion revetments. A bed-check weir was installed 123 m downstream of Harelaw Bridge in an attempt to halt the upstream propagation of bed incision (Figure 6.24). During the winter of 1953 a portion of the weir was breached and the adjoining riverbank failed, requiring extensive repairs. Further damage to this weir was reported in 1957 due to excessive gravel extraction in the vicinity of the weir to a

depth of 0.9 m. To prevent total failure of the weir additional bed-check weirs were installed immediately downstream.

Figure 6.24 Bed check weir, installed during 1953 at the head of the Wolsingham study reach, viewed in 2002. Harelaw Bridge can be seen in the background.



Reversion to a single thread planform occurred following the cessation of these gravel extraction operations. The channel in 1971 represented a considerable rationalisation since 1951 (Figure 6.25). Comparisons between the 1957 and 1971 aerial photographs (Figure 6.25) indicate the channel structure subsequent to extraction (1971) was generally the same as that in 1957, and with the exception of the former northern distributary, which was in-filled, the channel was allowed to adjust naturally. Despite the end of gravel extraction at Wolsingham in January 1960 problems associated with bed lowering persisted. Landscaping between January and July 1960 included further weir repairs, bank regrading and levelling of exposed gravel.

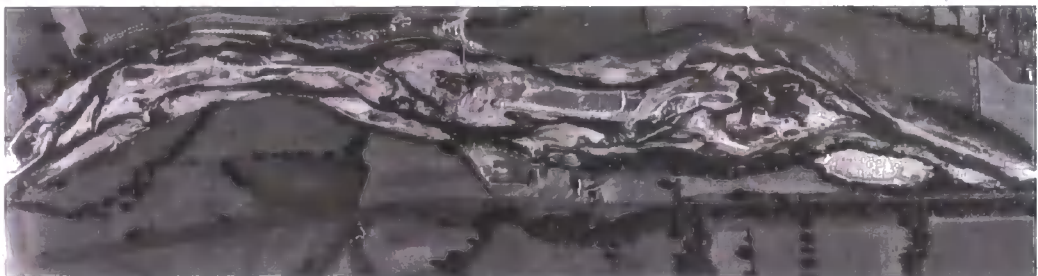
Channel changes subsequent to the cessation of extraction were strongly influenced by the channel structure produced by extraction operations (1957) (Figure 6.25). Of particular significance was the development of channel braiding, which formed in

response to gravel reworking. This reworking was promoted by a lack of vegetation on exposed surfaces and the disruption of the armoured layer of the channel bed. The abandonment of the braid zone, however, appears to have been encouraged by deposition of sediment in the location of channel division and suggests localised sediment reworking continued until the late 1970s. By 1971 vegetation colonisation had reached an advanced stage with vegetated or semi-vegetated gravel accounting for a larger proportion of bars than active bars (Figure 6.25).

The channel in 1991 showed the effects of continued vegetation colonisation and reduction in active bar extent (Figure 6.22 and 6.23). Many former bars became incorporated into the riverbanks and the divided zone in the central portion of the reach had been abandoned. Aerial photograph evidence suggests that bypassing of the braided zone was a relatively gradual process. By 1976 the majority of the flow had become routed through the distributary channels enlarging these, although the northern channel remained active. By 1978 all flow had become routed along the southern bank through the distributary channels, flow having ceased to be conveyed along the northern channel. By 1986 flow had become completely concentrated along the southern bank, the minor distributaries having now been abandoned as the channel widened along the southern bank.

Figure 6.25 Aerial photographs illustrating channel changes between 1951 and 1971 in the central portion of the Wolsingham reach. Flow is from left to right and the length of channel shown is 1 km (Source: RAF Aerial Photography (1951 and 1957) and ADAS Aerial Photography (1971)).

1951



1957



1971



6.3.8. *River Wear at Harperley Park*

At Harperley Park, channel planform change between 1844 and 1858 was coincident with artificial channel straightening. During construction of the Wear Valley Extension Railway (1846-1847) bends 1 and 2 (Figure 6.26 and 6.27) were removed. Channel engineering like this tends to promote channel changes downstream (Brookes, 1987). Removing bends increases channel gradient, which in turn increases stream power that results in enhanced bed erosion. A greater sediment load is then conveyed downstream to a point where the straightened section ends, gradient declines, and deposition occurs as the transport capacity of the flow falls (Knighton, 1998). The trebling of channel width downstream of bend 1 results from deposition within the channel and resulting bank erosion. The area of active gravel in the reach had increased substantially, primarily in the form of lateral bars (Figure 6.27). Bank erosion acts as an additional sediment source promoting further sedimentation, such as the channel division at point B. A similar channel response occurred below the former location of bend 2, where deposition coincided with bend growth at point C (Figure 6.27). Artificial channel straightening appears to have disrupted the channel but re-organisation was sufficient to re-establish equilibrium. Similarity in total channel sinuosity (cf. Hong and Davies, 1979) prior to channelization of 1.102 (1844) and subsequent to channel readjustment of 1.128 (1858) supports this view.

Only relatively minor channel changes occurred during the period between 1858 and 1896 (Figure 6.27) and the reach as a whole showed a slight decrease in the area of active gravel bars (Figure 6.27 and 6.28) due to vegetation colonisation in the upper portion. The area of mid-channel bars along the reach increased (Figure 6.27 and 6.28). The mid-channel bar at location B continued to grow. Channel division increased at Harperley Park between 1895 and 1919 in both the middle and lower portion of the reach (Figure 6.27). Channel division in the centre of the reach began with the detachment of the large left bank bar between points A and B and mid-channel bar development accompanied by channel widening in the lower part of the reach.

Figure 6.26 Channel planform change along the Harperley Park reach 1844-1991. Letters and numbers indicate locations referred to in the text. Flow is from top to bottom.

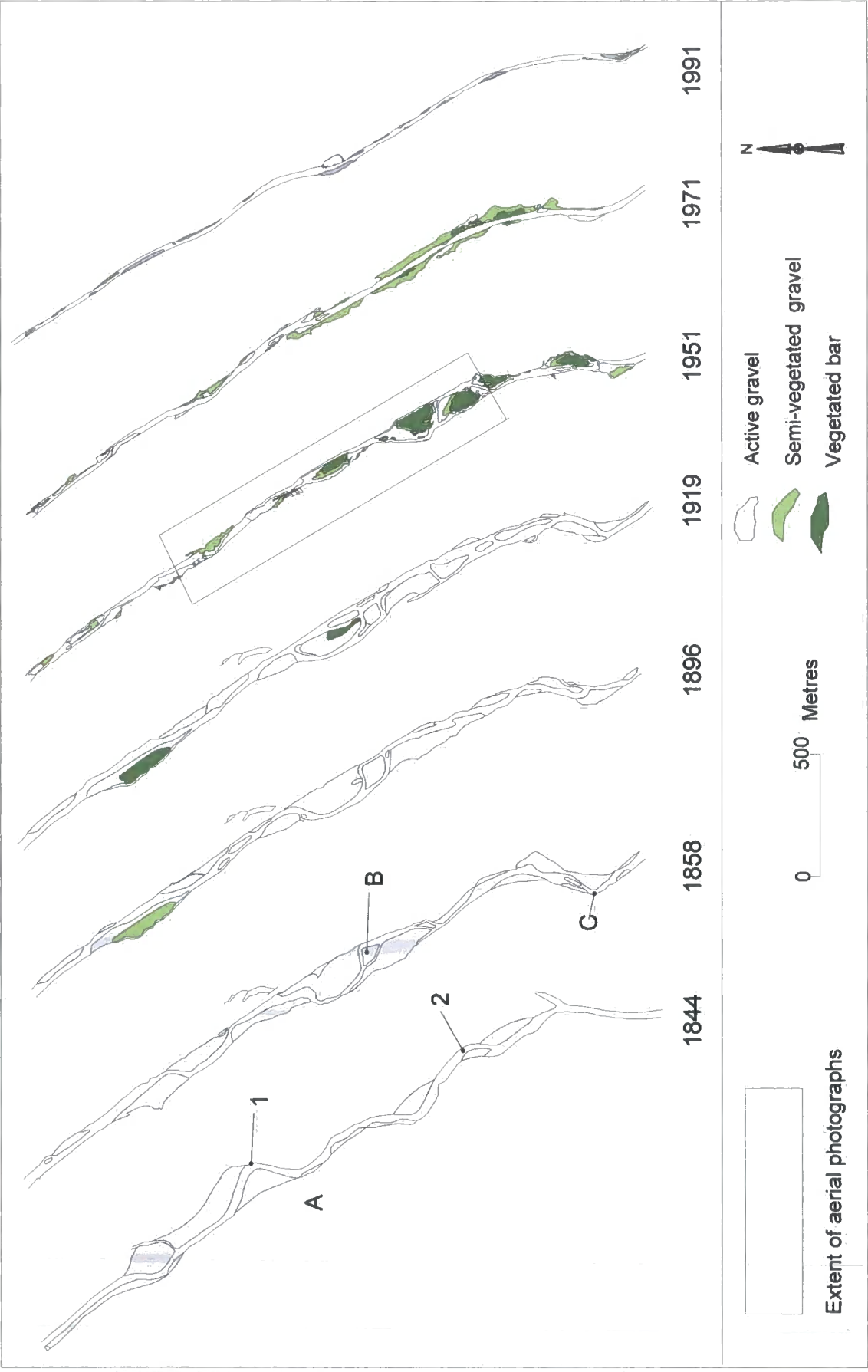
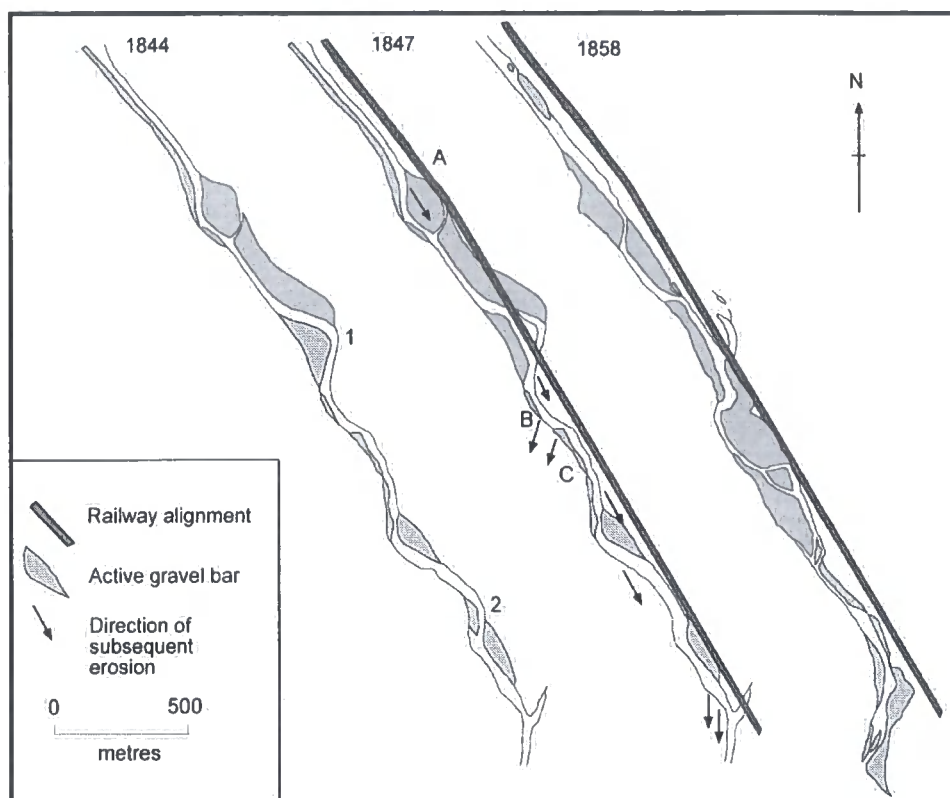


Figure 6.27 Channel planform development along the Harperley Park reach following channel engineering.



The channel at Harperley Park changed significantly between 1919 and 1951 while the significance of channel division continued to increase (Figure 6.27). As the total area of gravel bars continued to decline the area of mid-channel bars increased, indeed mid-channel bars were more extensive than lateral bars (Figure 6.27). In the middle portion of the reach considerable narrowing of the active channel occurred and much of the former left bank distributary channel and mid-channel bar became vegetated and attached to the right bank. In the lower portion of the reach mid-channel bar growth was accompanied by vegetation colonisation (Figure 6.27).

Between 1951 and 1971 the upper half of the reach showed only minor changes; chiefly a reduction in active gravel area. However, in the lower half of the reach significant changes in the river channel occurred. Here the flow was routed down a straight single thread channel. An aerial photograph taken of this reach in 1957 shows minimal changes occurred between 1951 and 1957, suggesting at this time there was no particular tendency for channel change (Figure 6.29). The dramatic channel changes, which occurred along the reach between 1951 and 1971, appear similar to those that occurred at Low Bat during the same period.

Figure 6.28. Change in bar area along the Harperley reach 1856-1991
 Note differing y-axis for mid-channel bars.

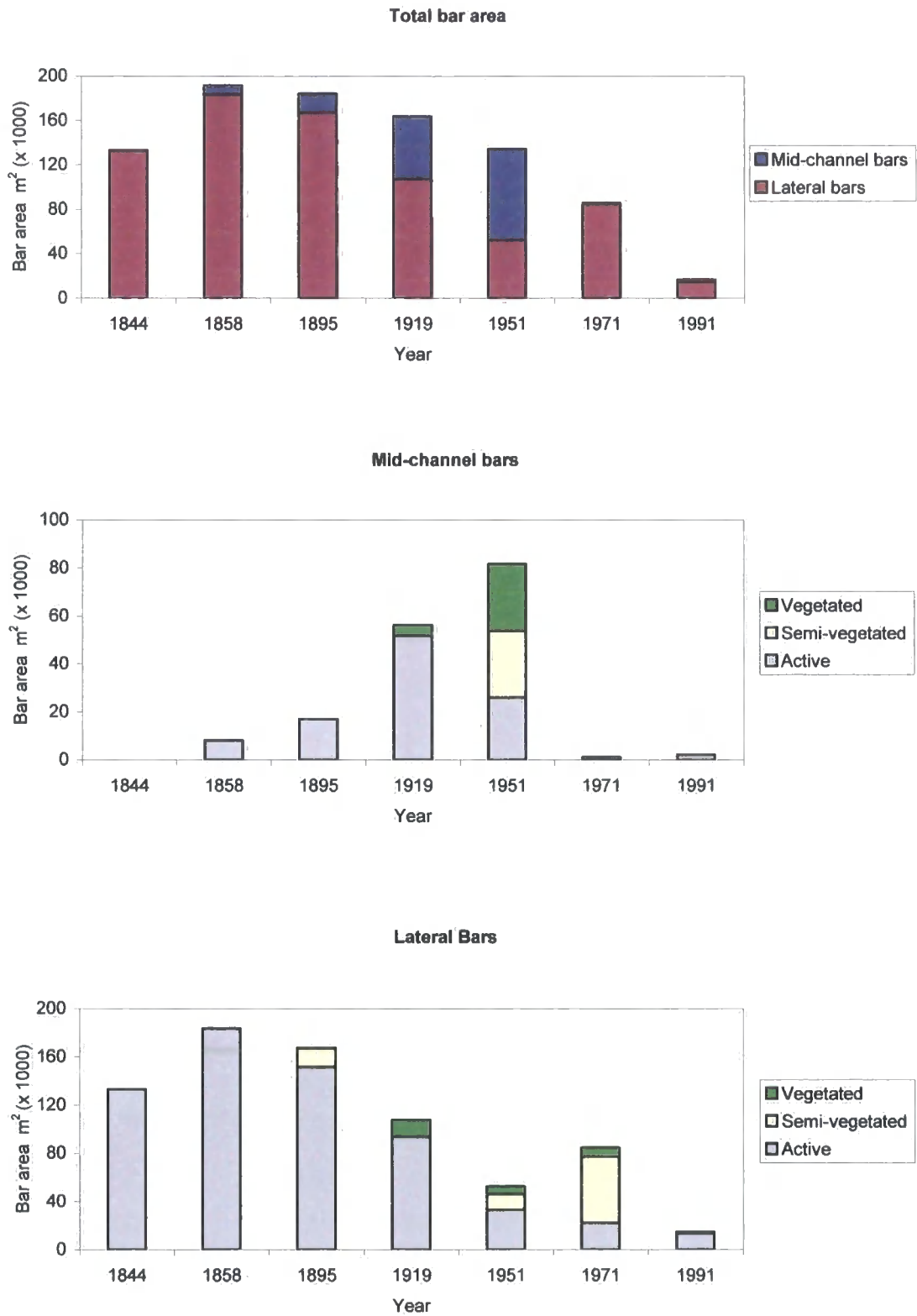
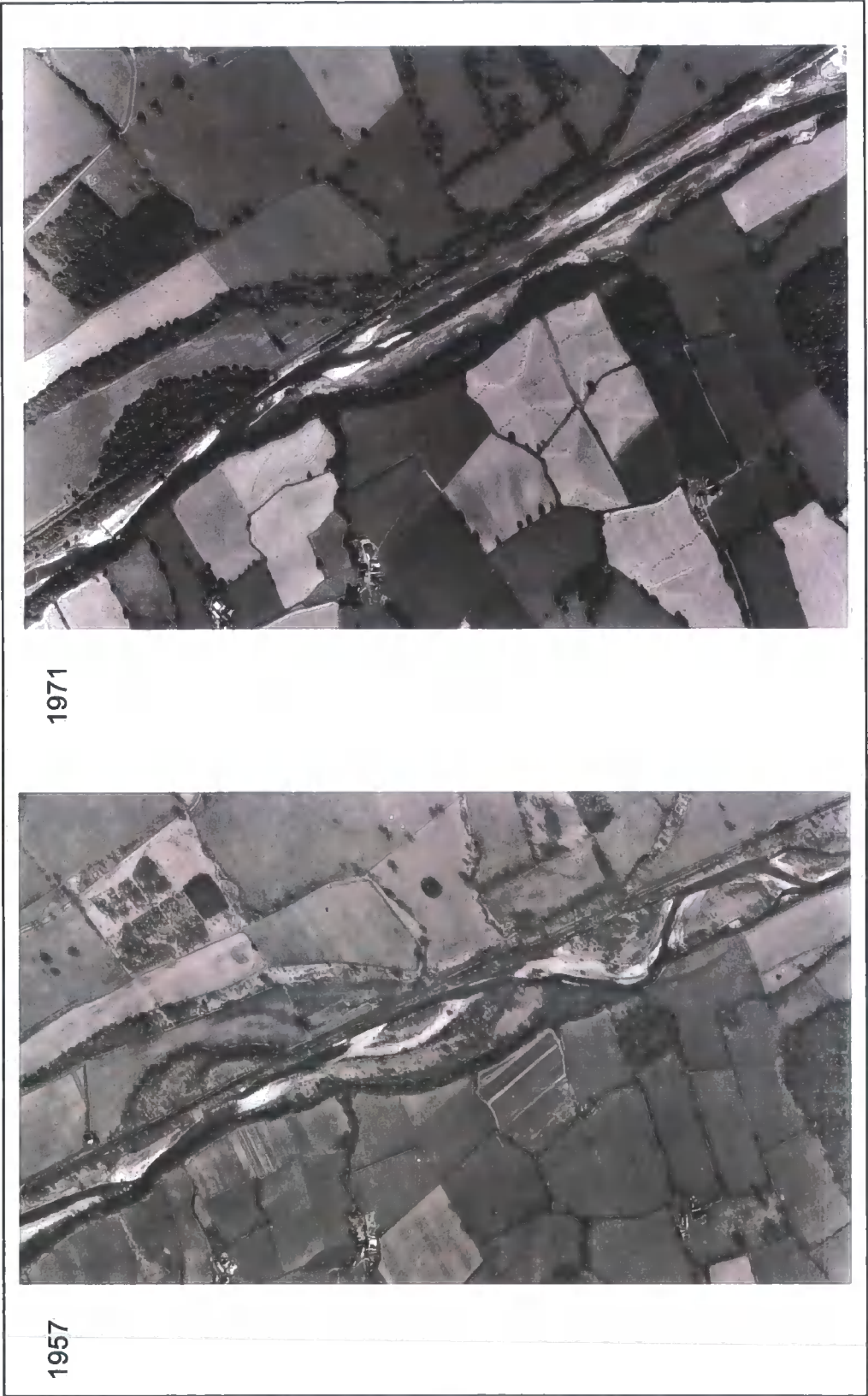


Figure 6.29 Comparison of channel planform along the Harperley Park reach in 1957 and 1971. Flow direction is from the top to bottom and the length of channel shown is 1 km (Source: RAF Aerial Photography (1951) and ADAS Aerial photography (1971)).



At Harperley, as at Wolsingham, there is good archival evidence that this was the result of gravel extraction operations. The gravel extraction technique employed at Harperley differed from that used at Wolsingham. At Harperley bars were removed sequentially by dragline moving progressively upstream, with flow diverted toward the right bank to maintain vehicular access. Production began in early 1961 and proceeded with an output in the region of 100,000 tonnes per year until 1968 when gravel availability was exhausted. Once gravel removal was completed the newly straightened channel was re-aligned in a central position (Figure 6.29). County Council records report fewer problems associated with extraction compared to Wolsingham. However, instructions were issued by the County Chief Engineer for the installation of a bed-check weir upstream of the extraction works. This followed concern about the potential upstream propagation of bed lowering damaging a footbridge. Although no figures are available for bed lowering, initial planning consent was given on the understanding that the new channel would not be greater than 0.9 m below the pre-existing bed level. The channel changes between 1957 and 1971 are illustrated in detail on Figure 6.29. The channel in 1971 was single thread with occasional small active lateral bars and extensive areas of vegetating lateral bars (Figure 6.28). Continued vegetation colonisation of lateral bars between 1971 and 1991 (Figure 6.27 and 6.28), resulted in the incorporation of the formerly semi-vegetated bars into the floodplain.

6.3.9. Summary

Each of the study reaches has shown a dramatic decline in the extent of active gravel bars over the period 1856-1991. The decline in bar extent was due principally to vegetation colonisation of the gravel bars. The significance of this decline is particularly evident when the percentage change in active bar area over the historic period is considered (Table 6.2). The declines in gravel bar extents varied considerably according to the initial extent of gravel bars. The percentage in bar area along the trunk channel is highly consistent despite the range of initial bar extents; indicating the reaches were behaving in a systematic manner. There is considerably less variation in the extent of gravel bars within each reach in 1991 compared to 1856, as is confirmed by the contrast in standard deviations of bar extent. This indicates the channels of the catchment were becoming increasingly uniform in extent, specifically as a result of changes in the extent of active bars. This confirms

the findings of the width series analysis and indicates the trend was also occurring in the tributary channels.

Table 6.2 Changes in the extent of active gravel bars within each study reach over the period 1856-1991.

Reach	Active gravel area 1856 (m ² x1000)	Active gravel area 1991 (m ² x1000)	Change in area (m ² x1000)	% Change
Ireshope	8.779	2.616	-6.163	70%
Bollihope	14.902	5.055	-9.847	66%
St John's Chapel	12.961	6.260	-6.701	52%
Brotherlee	64.721	8.253	-56.468	87%
Eastgate	95.750	9.572	-86.178	90%
Low Bat	62.015	7.850	-54.165	87%
Wolsingham	80.224	10.742	-69.482	87%
Harperley Park	132.899	15.402	-117.497	88%
Total	472.251	65.750	-406.501	
Mean	59.031	8.219	-50.812	
Standard deviation	44.546	3.876	40.895	

6.4. Implications

6.4.1. Reach-scale controls on river channel behaviour

In addition to the catchment-scale influences (principally flood frequency and magnitude and metal mining) a number of reach-specific factors also appear to govern channel planform change (Table 6.2). These range from localised anthropogenic activities such as hushing, quarrying, channel engineering and gravel extraction to climatic events such as intense convective storms. All of these resulted in deviations in channel behaviour from those recorded elsewhere in the catchment at that time. The duration of these controls varied from single years (storms) to decades (gravel extraction) and while these may have lead to short term variations in channel behaviour, over longer-time periods the channels have adjusted to reflect catchment-scale forcing. This is revealed clearly by the general decline in gravel bar extents along each of the study channels despite short-lived variations that were detected.

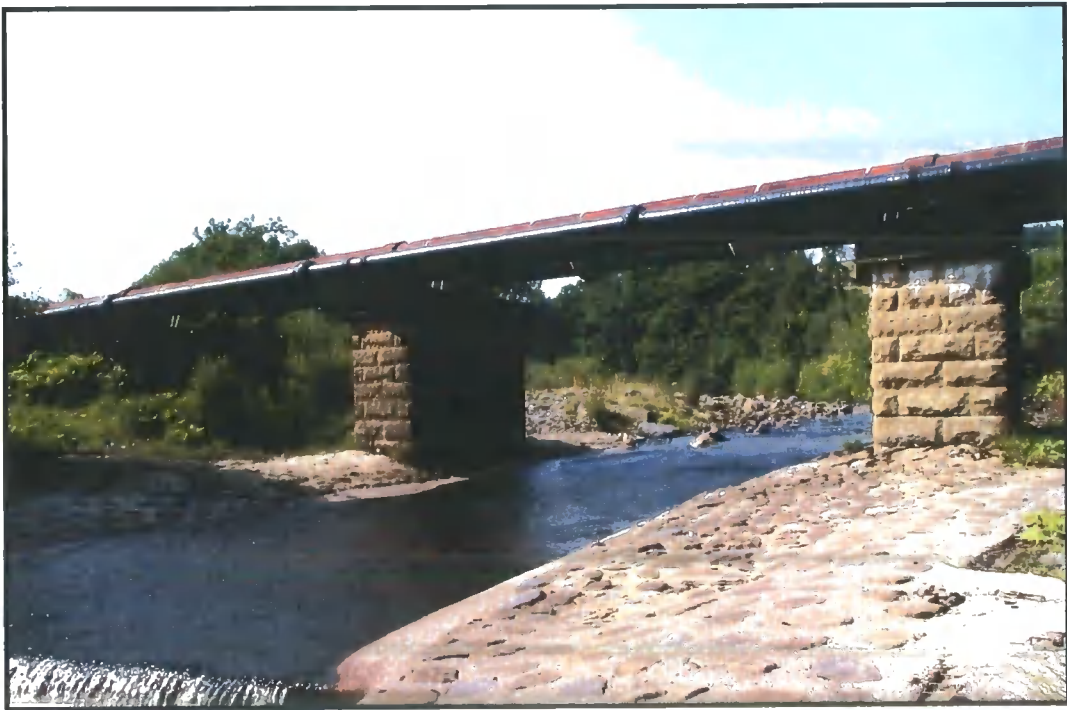
Table 6.3 The nature and period of influence of local controls on channel behaviour for reaches examined in Weardale.

Reach	Local controls detected	Duration of influence
Ireshope Burn	Hushing	Pre 1850
	Intense storm events	1900, 1903, 1983
Bollilhope Burn	Hushing	Pre 1850
	Quarrying	1850s-1950s
	Channel engineering	Around 1896
St John's Chapel	Bank protection and weirs	Recent
Brotherlee	Gravel extraction	1968
Eastgate	Possible channel engineering	Around 1890
Low Bat	Gravel extraction	Late 1960s
Wolsingham	Gravel extraction	1945-1960
Harperley Park	Channel re-alignment	1845
	Gravel extraction	1960-1968

Observations from Weardale suggest that anthropogenic channel interference tend to be concentrated into the sedimentation zones, although some smaller interference

may have occurred elsewhere. It appears that the active nature of the river channels in sedimentation zones encourages anthropogenic interference. Firstly the high lateral mobility of the channel in these settings can necessitate channel modification, such as straightening and weir construction (Figure 6.30). Secondly the extensive gravel bars of such reaches make them attractive locations for commercial gravel extraction operations. Of these activities, in-channel gravel extraction operations are considered to be extremely important as they resulted in the complete transformation of the river channel along both the Wolsingham and Harperley Park reaches. Such operations have serious impacts on channel stability along sections of river channels both upstream and downstream of extraction sites (Kondolf, 1997). Similarities in channel changes between Harperley Park and Low Bat (1951-1971), together with the weir construction at Low Bat, suggests gravel extraction operations were also carried out at Low Bat, although no archival material pertaining to these operations could be obtained. In context of the UK, the impact of gravel-extraction operations represents a relatively neglected area of research, despite its potential for causing significant changes in river channel stability (Sear and Archer, 1998). Because of its potential implications for river channel stability in lower Weardale during the late twentieth century the impact of gravel extraction is now considered in detail.

Figure 6.30 An example of a bed-check weir located in the St John s Chapel reach. The weir is sited to provide protection for the pipe crossing.



6.4.1.1. Gravel extraction and channel planform change

River channel adjustment in response to gravel extraction is regarded as a consequence of the disruption to the downstream sediment supply continuum (Sear and Archer, 1998). Kondolf (1993) argues that trapping of sediment within the lowered section of a riverbed leads to downstream incision due to an excess of stream power caused by sediment load depletion. Gravel extraction also disrupts the armoured structure of a riverbed, which also promotes bed erosion (Sear and Archer, 1998). In addition lowering the riverbed leads to a locally high bed gradient, which increases stream power and induces bed erosion and the development of knick points (Kondolf, 1997). Knick point development was particularly marked at Wolsingham.

The response of river channels to gravel extraction is generally considered to be primarily a function of the magnitude of the deficit in the sediment balance of the reach, which develops when sediment is extracted at a greater rate than it is supplied (Sear and Archer, 1998). The impacts of gravel extraction can be examined by establishing a sediment budget for the extraction reach. Sear and Archer (1998) attempted a simple sediment balance by subtracting the extracted yield from an estimate of the catchment sediment yield. Extraction yields recorded in archival sources provide estimates of quantities of material removed from the bed. Catchment bed load yields were derived from an empirical regression equation for catchments greater than 100 km² derived from a database of UK field measurements (Sear and Newson, 1991):

$$\text{Bed load (tonnes yr}^{-1}\text{)} = 2.50 a^{1.16} \quad (6.1)$$

where a is catchment area (km²).

Sear and Archer (1998) converted mass bed load yields to volumetric yields using the density of rock (2.65) enabling the estimate to be compared with extraction records. However, using a density of solid rock is misleading, as the sediment stored in the reach and extracted is unconsolidated gravel with a packing density of 1.8. In order to compare these volumetric results (m³) with extraction records obtained in this study (t yr⁻¹) the volumes of material extracted from rivers in Northern England (Sear and Archer, 1998, p429) were converted to tonnes assuming a packing density of 1.8 rather than 2.65 (Table 6.4). Because Sear and Archer converted catchment sediment yield to a volume using the packing density of rock (2.65) they reduced the

Table 6.4 Table summarising the results of sediment balance calculations for gravel extraction data from rivers in Northern England based on data modified from Sear and Archer (1998, p 429).

River	Extraction site	Catchment area km ²	Catchment sediment yield (t yr ⁻¹)	Extraction yield (t yr ⁻¹)	Ratio** Extracted: Yield	Ratio*** calculated by Sear and Archer (1998)
Swale	Langton Bridge	630	4417.5	825,687	187	275
Wear*	Wolsingham*	255	1547.1	36,000	23	-
Wear*	Harperley*	328	2072	100,000	48	-
Wear	Witton	455	3028.5	131,481	43	64
Tyne	(All sites)	2,000	16,870.8	167,024	10	14
Coquet	Hepple	346	2,204.3	81,000	37	54
Wooler Water	Haugh Head	48	382.7	57,875	151	222
Breamish	Ingram	103	540.5	72,000	133	126

* This study

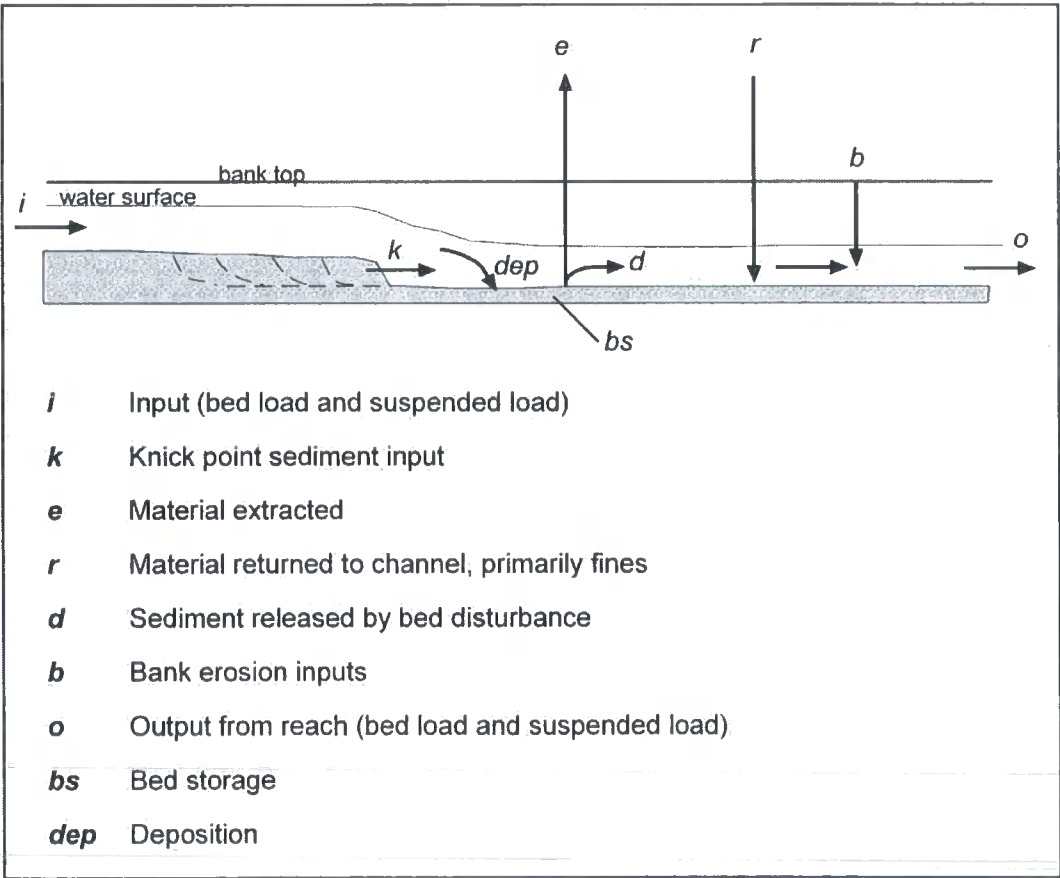
** Calculated by dividing the extraction yield by the catchment sediment yield

*** Ratio calculated by Sear and Archer (1998) using the packing density of rock to determine catchment sediment yields

sediment yield of the catchment. As no such conversion was undertaken in this study the catchment sediment yields are higher, reducing the ratio of extracted gravel to sediment transport yield (Table 6.4).

However, reports of gravel extraction in this study and others indicate a range of additional variables that should be added to the reach-based sediment budget summarised in Figure 6.31. In particular, when constructing a sediment budget for gravel transfer through an extraction reach, additional sediment delivered to the reach by bank erosion and knick point migration must be accounted for. Bank erosion can be measured from aerial photographs where bank heights are known. In the case of both Wolsingham and Harperley Park, however, average bank erosion inputs were negligible. Both gravel extraction and knick point recession remove material from bed storage. Where the depth and extent of incision is known, knick point sediment yield can be estimated. Bed storage within the reach changes over time in response to deposition and removal by extraction and knick point migration.

Figure 6.31 Schematic diagram illustrating the components of a sediment budget for a reach subject to gravel extraction.



Accounting for these factors the bed load sediment budget can be calculated as follows:

$$o = i + b + \Delta bs \quad (6.2)$$

where i is the input of bed load, b is bank erosion inputs and Δbs is change in bed storage. Change in bed storage is calculated using:

$$\Delta bs = dep - e + k \quad (6.3)$$

where dep is deposition, e is the extracted yield and k is knick point sediment loss.

Although the efficiency of bed load transport through the reach is unknown, increased channel width and increased potential storage in pits suggest a proportion of the bed load will be deposited. Additionally, bedload transport is discontinuous and involves continual exchange between mobile sediment and deposits (Church et al., 2001). The calculation therefore assumes the majority of bed load input to the reach in a given year is deposited on the channel bed and is available for extraction. This is supported by the historic maps, which indicate that the Wolsingham and Harperley Park reaches were sites of net sediment storage between the mid-nineteenth and mid-twentieth centuries. Several other extraction sites in Northern England were also sites of net sediment storage (Sear and Archer, 1998). Estimates of each component of the budget have been made for both reaches (Table 6.5). Knick point recession of up to 500 m was recorded at Wolsingham, however in 1953 the installation of a bed-check weir prevented further sediment inputs from knick point recession. The budget for Wolsingham has been calculated both for the period 1947-1953, during knick point recession and following the installation of the weir. The bed load budgets show a deficit of 17,905 t yr⁻¹ during knick point recession at Wolsingham, which increased to 32,905 t yr⁻¹ following bed-check weir installation. At Harperley Park where no knick point erosion was recorded the budget shows a deficit of 95,856 t yr⁻¹. Knick point sediment inputs can have significant impact on the sediment budget of an extracted reach, significantly reducing the deficit in the sediment budget.

Even if it is assumed that the entire annual bed load is deposited within the reaches this forms a minor component of the budget overall. To sustain extraction at these rates a significant proportion of the extracted sediment must have been removed from long-term storage elements within the river channel. Both Wolsingham and Harperley Park have been sites of net gravel storage since the nineteenth century,

much of this in relatively stable vegetated bars. Gravel extraction disrupted these bars producing a rapid increase in sediment delivery to the channel bed during the early stages of gravel extraction. This sudden increase in deposition, which would have reduced the sediment deficit, is not accounted for in the sediment budget (Table 6.5). Similar fluxes of sediment to bed storage may also have occurred during flood events. The bed load sediment budget described above demonstrates that bed storage is a key element of the sediment budget. In the case of this study uncertainties remain regarding the change in sediment storage, particularly rates of bed sedimentation which may have increased during extraction operations due to channel widening and the presence of settling ponds.

At Wolsingham it is known that significant quantities of fine sediment were released during extraction and on-site gravel processing (d and r in Figure 6.31). The significance of this can also be assessed within the sediment budget by comparing the volume of fine sediment supplied from the catchment to that released from the reach. Fine sediment delivery to the reach can also be estimated using the empirical yield regression equation for catchments greater than 100 km² derived from a UK database of field measurements (Sear and Newson, 1991):

$$\text{Suspended load (tonnes yr}^{-1}\text{)} = 31.04 a^{1.04} \quad (6.4)$$

where a is catchment area (km²).

The volume of fine sediment released can be estimated by calculating the proportion of bed sediment that can be transported in suspension (fraction < 2 mm). From bulk samples of bed material obtained from the two sites, estimates are 10 % at Wolsingham and 11% at Harperley Park. This percentage is then subtracted from the extraction yield to give an estimate of potential fine sediment release during extraction. The sediment budget for fine sediment transport through the reach can be calculated for each reach:

$$o = i + (d + r) \quad (6.5)$$

Table 6.5 Values of sediment budget components calculated for each reach. Separate budgets have been calculated for the Wolsingham reach during knick point recession and following bed check weir installation.

Annual sediment quantities (tonnes yr ⁻¹)				
	Component of budget	Wolsingham		
		During knick point recession	Subsequent to knick point recession	Harperley Park No nick point recession
Bed load	Catchment Input (<i>i</i>)	1547.1	1547.1	2072
	Bank erosion inputs (<i>b</i>)	0	0	0
	Deposition (<i>dep</i>)	1547.1	1547.1	2072
	Extraction (<i>e</i>)	36000	36000	100000
	Knick point inputs (<i>k</i>)	15000	0	0
	Sediment balance	-17905.8	-32905.8	-95856
Suspended sediment	Catchment Input (<i>i</i>)	9879.2	9879.2	12836
	Material liberated (<i>d</i> and <i>r</i>)	3600	3600	11000
	Sediment balance	13479.2	13479.2	23836
Combined	Reach sediment budget	-4426.6	-19426.6	-72020

The budget shows that gravel extraction increases the fine sediment output from both reaches from $9,879 \text{ t yr}^{-1}$ to $13,479.2 \text{ t yr}^{-1}$ at Wolsingham and from $12,836 \text{ t yr}^{-1}$ to $23,836 \text{ t yr}^{-1}$ at Harperley Park (Table 6.5). When the suspended sediment budget is combined with the bed load budget, the sediment budgets for each show a negative budget. Despite the suspended sediment yield from the catchment being significantly greater than the bed load yield and the liberation of additional suspended sediment during gravel extraction, this does not compensate for the loss of coarse sediment due to extraction (Table 6.5).

The sediment budgets described above outline the components necessary to produce a sediment budget for reaches affected by gravel extraction. The uncertainties identified in these examples demonstrate the need for detailed process monitoring during the extraction operations. Of particular concern are uncertainties surrounding the applicability of using generalised equations to determine catchment sediment yield (Equations 6.1 and 6.4). The equations assume that bed load yield increases with catchment area, however the historical studies have demonstrated that significant quantities of sediment are stored in the sedimentation zones and that catchment sediment yields have varied. It is therefore inappropriate to assume sediment yield is purely a function of catchment area or that all material yielded by the catchment reaches the extracted reach. Rates of sedimentation within the reach from both the disruption of long-term storage elements and from the catchment beyond must be carefully monitored, in order to establish the bed load sediment balance. Bed load budgets are particularly important, as bed sediment is that which mainly determines the morphology of the river channel (Church et al., 2001). Nevertheless, despite these limitations the sediment budgets yield important insights into the cause of channel adjustment due to gravel extraction and the importance of morphological responses.

Gravel extraction operations at Wolsingham and Harperley Park were responsible for the most dramatic planform changes to affect both reaches during the 150-year period of this study. The upstream progression of incision evident at Wolsingham is consistent with observations from channel gravel extraction sites in the United States (Kondolf, 1997). Incision upstream of Harperley Park is not well documented in the archival sources and field evidence indicates knick point development did not develop to any degree. Downstream incision described by Kondolf (1993, 1997) is not evident at either site. Conversely channel division in 1971 at Wolsingham (Figure 6.22) and lateral bar growth in the lower reaches of Harperley Park indicate

downstream sedimentation. Downstream sedimentation at Wolsingham generated a localised zone of channel division, which was gradually abandoned during the 1970s. On the basis of aerial photograph evidence, this abandonment occurred due to sedimentation in the mouth of the northern distributary channels. Gradual abandonment of distributary channels is supported by the lack of large floods during the 1970s (Figure 4.8). At Harperley Park aerial photograph evidence suggests that sedimentation occurred later, with field evidence indicating recent sedimentation in the reach, perhaps due to the large flood in 1995.

At Wolsingham both incision and downstream sedimentation were more extensive than at Harperley, implying that incision is a significant source of sediment for downstream sedimentation. Based on both simple extraction deficits (Table 6.4) and the sediment budget calculations (Table 6.5) more substantial impacts would be expected at Harperley Park. Despite the longer period of extraction at Wolsingham (15 years) as opposed to 8 years at Harperley Park, a greater quantity of material was removed at Harperley (800,000 tonnes) than at Wolsingham (540,000 tonnes). At Wolsingham geomorphic impacts were both erosional (upstream incision) and depositional (downstream deposition), whereas at Harperley Park impacts were restricted to longer-term deposition. Two explanations may be invoked. Firstly large volumes of sediment, contained in vegetated mid-channel bars, were reactivated and added to bed storage during extraction operations, thus reducing the local sediment deficit at Harperley Park. Secondly the technique used to extract gravel may also have influenced the magnitude of channel response. At Harperley Park a new channel was excavated during gravel extraction with an even bed gradient designed to merge with the undisturbed upstream reach. At Wolsingham the channel was allowed to adjust naturally, while abrupt changes in bed topography associated with pit excavations may have acted as the loci for bed erosion that progressed upstream.

The sediment budget has demonstrated that the development and migration of a knick point can increase sediment supply to the site of extraction. However installation of bed check weirs substantially decreases the sediment input from upstream. In the broader context knick point recession may be considered as a mechanism of sediment loss, or at least remobilisation, at the larger scale. The excavation of a carefully graded channel at Harperley appears to have prevented knick point development, reducing upstream incision and hence sediment availability within the reach. However the lower channel gradient of the Harperley Park (0.004 compared to 0.006 at Wolsingham) may also have limited the potential for knick point

formation. Sedimentation occurred much later, during large floods such as those of 1991 and 1995 (Figure 4.8). In this respect, channel response to gravel extraction appears to be sensitive to the technique of gravel extraction in addition to the volume of material removed. Gravel extraction operations through pit excavation and repeated channel re-routing (Wolsingham) produced greater problems than downstream dragline extraction and channel restoration (Harperley Park).

Channel planform changes in the years subsequent to anthropogenic activity demonstrate that planform recovery is controlled by flood frequency and magnitude. Observations at Wolsingham have shown the 1960s bed-check weirs have been destroyed by recent flooding. Aerial photograph evidence reveals, however, that they were all intact in 1991. This suggests the channel is still responding to gravel extraction impacts. A particularly large flood in 1995 (Figure 4.8) may have contributed to weir destruction. The first weir (1953) remains in position, but a large breach has occurred on the right bank side of the weir and elsewhere the weir is badly damaged (Figure 6.24). This is now deflecting flow against the right bank, which has resulted in the collapse of the 1953 bank protection works. Perhaps more significantly, lowering of the riverbed is now beginning on the upstream side of the weir (Figure 6.24). The weir is now unstable and liable to continued failure during high flow events. Should the weir be washed-out, bed lowering of approximately 1 m, can be expected to propagate upstream.

Of particular concern, in view of the significance of flood events, is the impact that climate change may have on the catchment. Predictions indicate that seasonal flooding can be expected to increase in both frequency and magnitude in response to climate change (Beven, 1993). This presents a potentially serious scenario for both reaches. The deterioration of the remedial structures at Wolsingham occurred during a period of comparatively low flood frequency and magnitude (Figures 4.8). Increased flooding is likely to further reduce the life span of remedial structures and those that have begun to fail, as at Wolsingham, can be expected to fail entirely. Bed incision can therefore be expected to increase within each reach, potentially down to bedrock, which is approximately 1 m below the channel bed. Increased incision in combination with increased flooding is likely to enhance bank erosion rates, as increasing bank heights will promote instability. Upstream incision however will be restricted by bedrock, which outcrops along the channel bed 200 m upstream of the Wolsingham reach.

6.5 Conclusion

This chapter has both reaffirmed the significance of climate-induced changes in flood frequency and magnitude and has demonstrated that reach-specific influences can also be important. However the occurrence of reach-specific controls occurred over shorter time intervals, typically years to decades, and resulting planform changes are similarly limited in duration. The most significant reach-scale influence is commercial gravel extraction that has significant channel impacts lasting up to 30 years. Ultimately however, this produces a channel planform consistent with that elsewhere in the catchment that resulted from a general decline in flood frequency and magnitude during the twentieth century.

1. Each of the study reaches was characterised by extensive gravel bars during the nineteenth century, the extent of which peaked earlier in the upper catchment and middle catchment than in the lower catchment. These then showed a progressive decline in the extent of active gravel from the mid-nineteenth century in the upper catchment and the late nineteenth century in the lower catchment, due to a decline in flood frequency and magnitude.
2. In the lower catchment in-channel gravel extraction operations were found to be responsible for a dramatic reduction in planform complexity and the extent of gravel bars. Three reaches appear to have been influenced in such a manner – Low Bat, Wolsingham and Harperley Park. The extensive nature of these operations indicates that this may be an important control on channel planform elsewhere in British gravel-bed rivers. A sediment budget approach has been developed which enables the impact of gravel extraction operations to be quantified. However in Weardale widespread channel degradation following gravel extraction appears to have been prevented by a combination of bed-rock control (Wolsingham), the technique of extraction (Harperley) and weir installation (Wolsingham and Low Bat).
3. Tributary channels are sensitive to localised convectional storm events which can occur irrespective of the prevailing climate regime and can lead to localised increases in the extent of gravel bars within tributary channels (Ireshope).

4. This chapter has illustrated the importance of local (reach-scale) influences. Yet the coincidence of the timing of sedimentation and its subsequent decline suggests over century timescales catchment-scale processes (climate) determine the behaviour of river channel planform. However, this can be influenced by reach-scale processes, which either enhance climate-induced changes (gravel extraction) or counteract regional trends (storm events).
5. Reaches can be representative of trends occurring at the catchment-scale, but the widespread nature of localised controls cautions against relying on the examination of a limited number of study reaches. Local controls can both enhance or reduce the impact of climate controls and can completely obscure climate controls over decadal timescales.

The detailed analysis of selected study reaches conducted by this chapter supports the findings of chapter 4 concerning the changes in the nature of sediment transfers through the catchment between 1856 and 1991. Importantly however, additional detail has been revealed concerning the timing of nineteenth century sedimentation. Sedimentation dates to the early nineteenth century (or perhaps earlier) in the upper and middle catchment and to the mid to late nineteenth century in the lower catchment. The results have also confirmed the persistence of localised sediment transfers within the catchment over the period 1896-1951 and demonstrated that locally these continued until the 1970s. Sediment transfers and associated changes in channel planform appear to be related to a combination of flood frequency and magnitude and reach-specific factors.

Chapter 7

Controls on channel structure and historic planform change in upper Teesdale

7.1. Scope of chapter

This chapter considers channel planform change in the upper catchment of the River Tees in upper Teesdale. The study is designed to assess the wider significance of the river channel planform changes that occurred in Weardale during the last 150 years. In Weardale the decline in lateral instability and the extent of active gravel during the twentieth century appears to be governed by a combination of flood frequency and magnitude, changes in catchment land use, specifically metal mining, together with direct modification of the river channel. The River Tees in upper Teesdale provides an important opportunity for further analysis because the contemporary channel structure is characterised by reaches showing channel division and extensive gravel bars, which appear to be similar to those found in Weardale during the nineteenth century. This not only provides a potential analogue for river behaviour during the nineteenth century in Weardale it also raises the question as to why the upper Tees appears to be unstable whilst channels in Weardale are largely stabilised. In addition, despite a long history of river study the Tees and Wear catchments have rarely been compared directly.

This chapter has three components; first the contemporary channel width series structure is examined along the trunk channel of the catchment (cf. Weardale). The impact of channel gradient is also considered because these study reaches were of a more variable gradient than those in Weardale. Nested within this, the historical sequence of channel planform change is examined along four reaches that are subject to both contemporary sedimentation and channel division. Finally the impact of a large flood event (30 July 2002) on channel planform is examined, particularly in relation to two reaches within the upper portion of the study area. The 2002 flood, generated by a convective storm, offered the opportunity to evaluate the importance of large floods as mechanisms of channel planform change.

7.2. Channel width series

Contemporary channel width series data was collected during 2002, from a study reach 5.9 kilometres in length located through the trunk of the upper Tees catchment (Figure 3.12). Contemporary channels (fourth order and above) in the catchment have a planform structure similar to that of the Wear during the nineteenth and early twentieth centuries; namely reaches of high channel width characterised by extensive bars, separated by relatively narrow reaches with fewer and smaller bars. The upper half of the catchment is characterised by two sub-catchments with wide fourth order trunk channels: the headwater catchment of the River Tees and the Trout Beck catchment (Figure 3.12). Two reaches of Trout Beck were known to have experienced contemporary and historic channel planform change and for this reason it was decided to begin the width series along Trout Beck. Downstream of the confluence between Trout Beck and the River Tees, the Tees dominates the catchment with only low order streams joining. As described in chapter 3, channel width measurements were recorded every 20 metres to determine the spatial variability of channel characteristics. The 20 m measurement interval represents a higher sampling resolution than that undertaken in Weardale (50 metres) because Trout Beck is a lower order channel than the River Wear and shows greater variability over shorter distances. The total channel distance measured at 5.9 km is considerably shorter than for the Wear (31 km) so using a 20 metre resolution increases the size of the data set allowing greater confidence in the statistical tests.

7.2.1 Channel width series along Trout Beck and the River Tees

The contemporary channel width series structure along the study reach is dominated by alternations between wide and narrow reaches (Figure 7.1). This is particularly well represented by total channel width (across channel belt) (Figure 7.2a). This planform structure is similar to that of the River Wear during the nineteenth century but the extent of vegetating bars makes the channel structure more akin to that of 1951. Observations made from contemporary and historic maps and aerial photographs (discussed in section 7.3) indicate that four principle sedimentation zones can be identified (Figure 7.2b), two along Trout Beck and two on the River Tees. Unlike Weardale the sedimentation zones of the River Tees are dominated by large vegetated islands. These appear to be completely stable as they are entirely covered by grass with a thin soil and lie at a higher elevation than the surrounding

Figure 7.1 Channel width structure along Trout Beck and the River Tees. Letters a-d indicate locations referred to in the text.

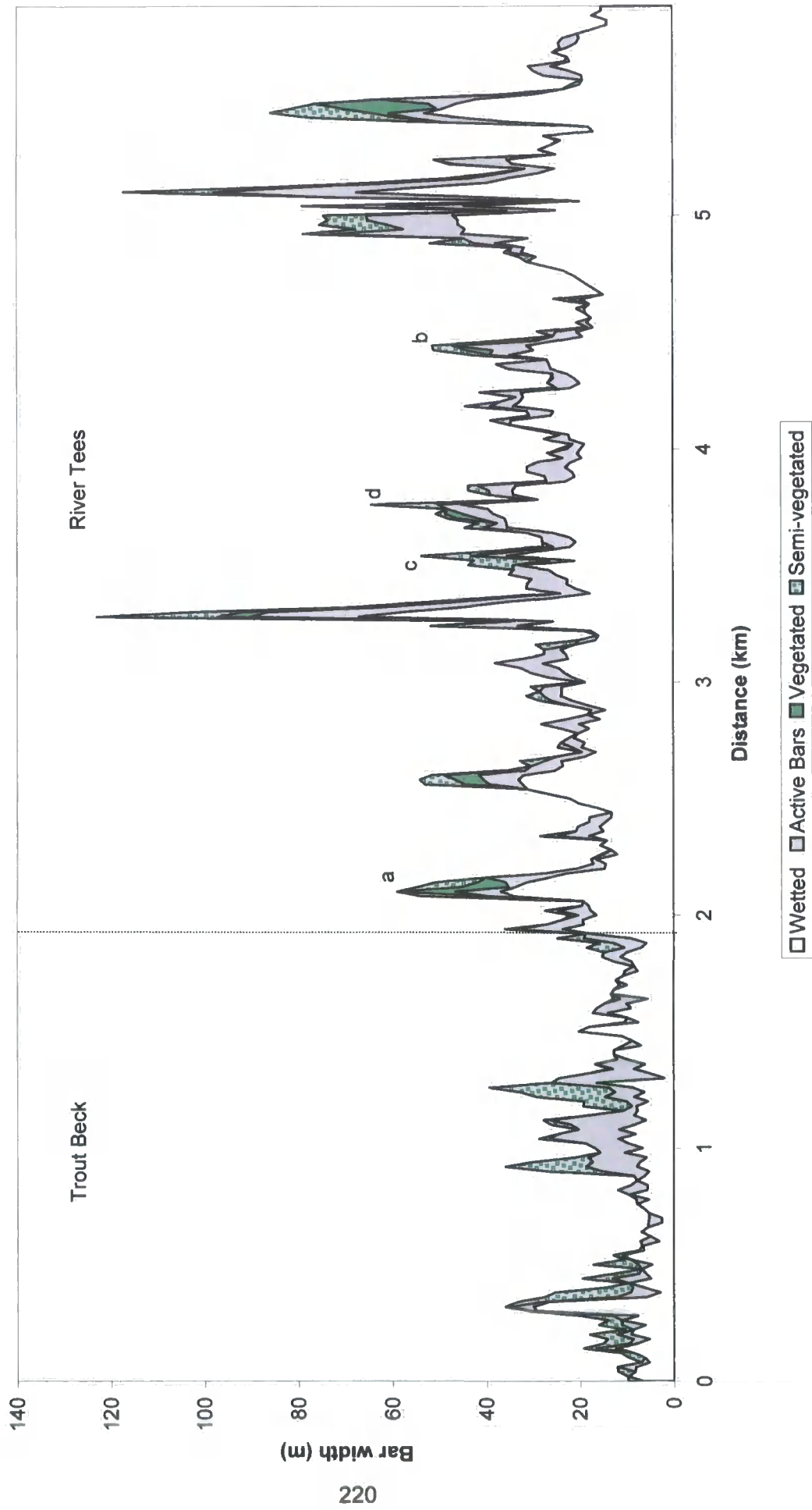
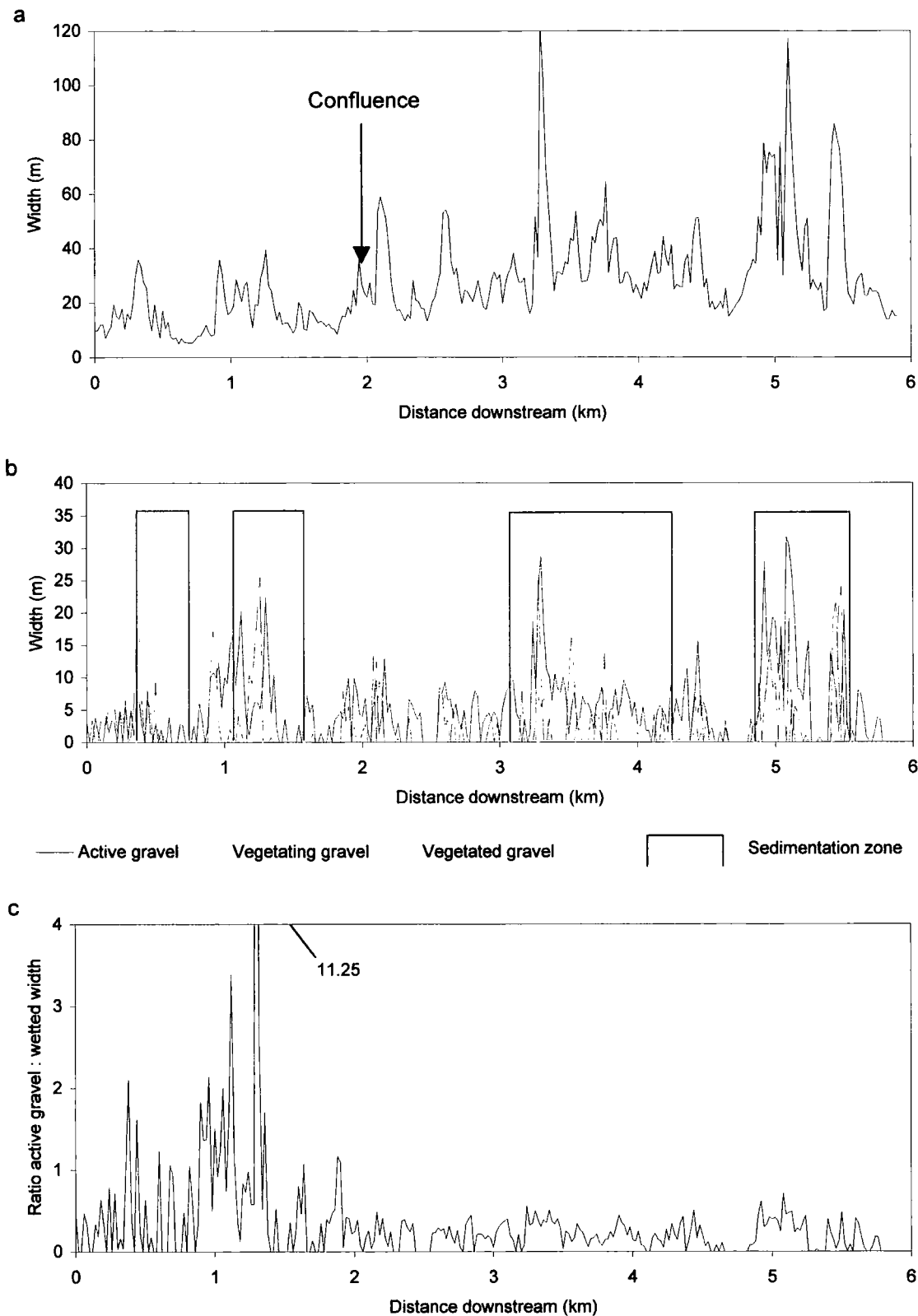


Figure 7.2 Channel structure: (a) total channel width (channel belt), (b) gravel bar widths and (c) ratio of gravel bar width to wetted channel width.



active bars (Figure 7.3). Indeed, historical evidence (described in section 7.3) indicates these bars have changed little over the past 50 years. As these are not components of the contemporary active channel they were excluded from the analysis. Flow separation around these islands has resulted in wide wetted channel widths in the locations a, b, c and d (Figure 7.1).

Figure 7.3 A large vegetated island in the River Tees at Crookburn Foot, flow is from left to right.



The ratio of exposed active gravel bar width to wetted channel width along the study reaches (Figure 7.2b) reveals that the high total channel width of these sedimentation zones is not maintained simply by active bars, but that vegetating gravel bars form a significant component of the channel planform in each reach. The ratio of active gravel to wetted channel width shows a marked contrast between the Trout Beck (0-1.9 km) and Tees sections (Figure 7.2c). The Trout Beck sedimentation zones are characterised by the occurrence of bar widths greater than the wetted channel width (ratio >1) (Figure 7.2b). However the River Tees is characterised by wetted channel widths typically twice that of gravel bars (Figure 7.2c). This suggests that the Tees experiences comparatively low rates of contemporary sedimentation.

Channel gradients are steep and vary from approximately 1 degree (0.017) to 3.5 degrees (0.016) which reflects the location of the study section within the headwaters of the River Tees. Generally, total channel width declines as gradient increases, with wide reaches located where the channel gradient is low (Figure 7.4 and Figure 7.5a). The section of channel with a gradient of 3.5 degrees (0.016) (Figure 7.4 and 7.5) represents a sharp drop in the channel bed due to the presence of waterfalls which result from an outcrop of the Whin Sill (dolerite intrusion). The relatively wide top widths are also associated with this bedrock outcrop (Figure 7.5). The relationship between total channel width and gradient is the result of preferential sediment deposition within the channel where gradient is low. This is confirmed by the relationship between total bar width and gradient (Figure 7.4). However, strong bedrock and valley structure control has prevented full alluvial adjustment to gradient, resulting in the wide scatter in the relationship between channel form and gradient. In addition bank heights were also measured along the study reaches, but these do not show any relationship with gradient (Figure 7.5c).

Time series analysis techniques identical to those used to examine the Weardale width series were applied to the Teesdale width series. This involved the autocorrelation and spectral analysis techniques described in Chapter 5 (refer to section 5.3.5 for an explanation of these techniques). These were calculated for total channel width, detrended using quadratic regression (Figure 7.6a) over the whole series for up to 40 lags. The autocorrelations are statistically significant for 4 lags (Figure 7.6b) and suggest that the channel widths are of a similar magnitude over distances of 80 m. However, in detail the correlation declines rapidly, signifying that channel widths decline over this distance.

The spectral density function (Figure 7.6c) reveals that the greatest variation in the width series occurs at low frequency, while small changes occur at higher frequencies. This means that the variation in channel width is greater over long distances (low frequency) than short distances (high frequency), which are characterised by relatively small variations in total width. This structure is similar to Weardale over the period 1856-1951 (Chapter 5). The complexity of the line (Figure 7.6c) is caused by local variation in channel width within the wide and narrow reaches. The difference between the widest and narrowest reaches is greater than the variation within either of the two channel types (small variations within these channel types occurs more frequently than variations between them). There is however a notable change in the gradient of the line of the spectral density function

Figure 7.4 Change in total width relative to variation in channel gradient.

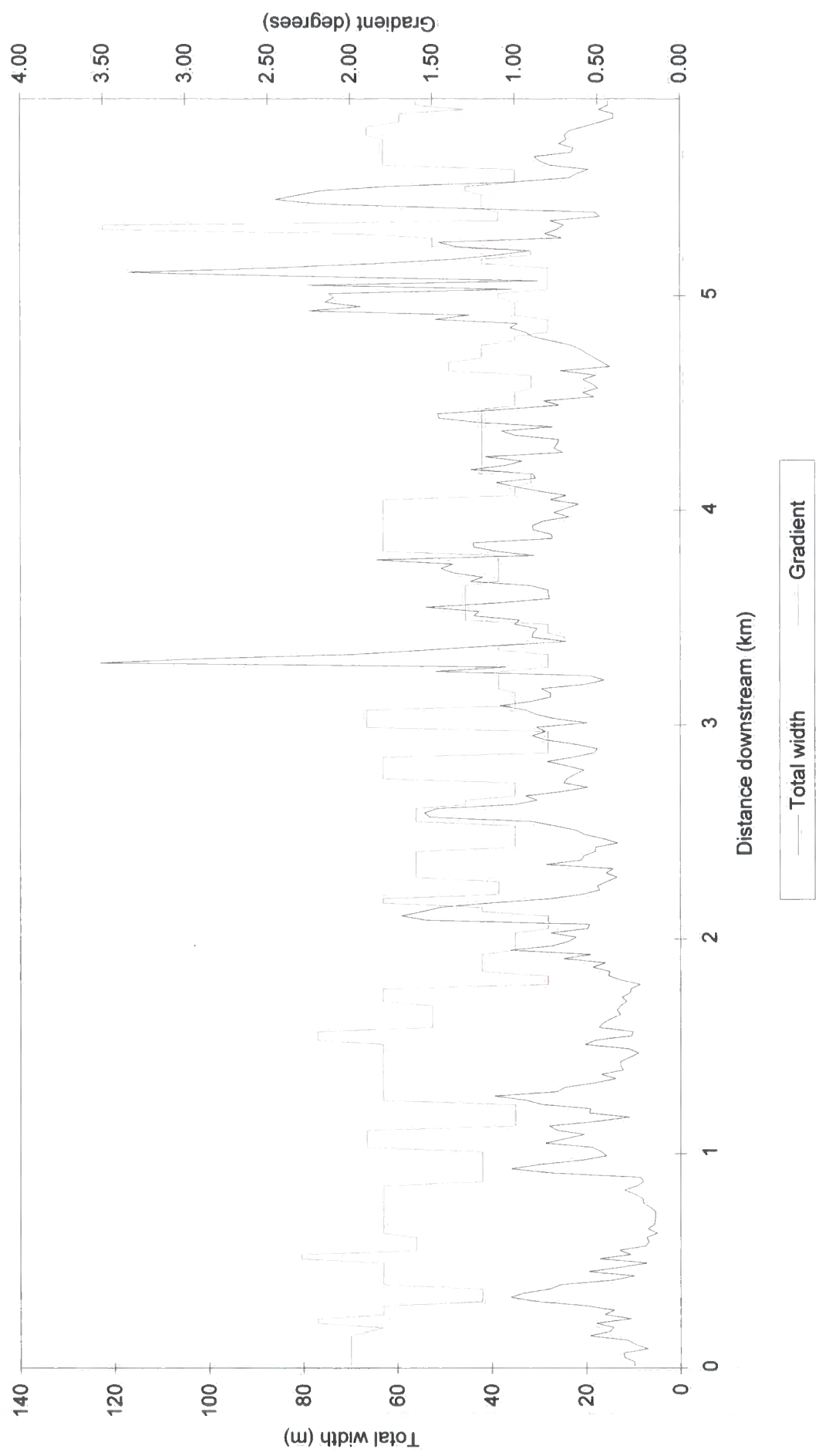


Figure 7.5 The influence of channel gradient on (a) total width, (b) total bar width and (c) bank height

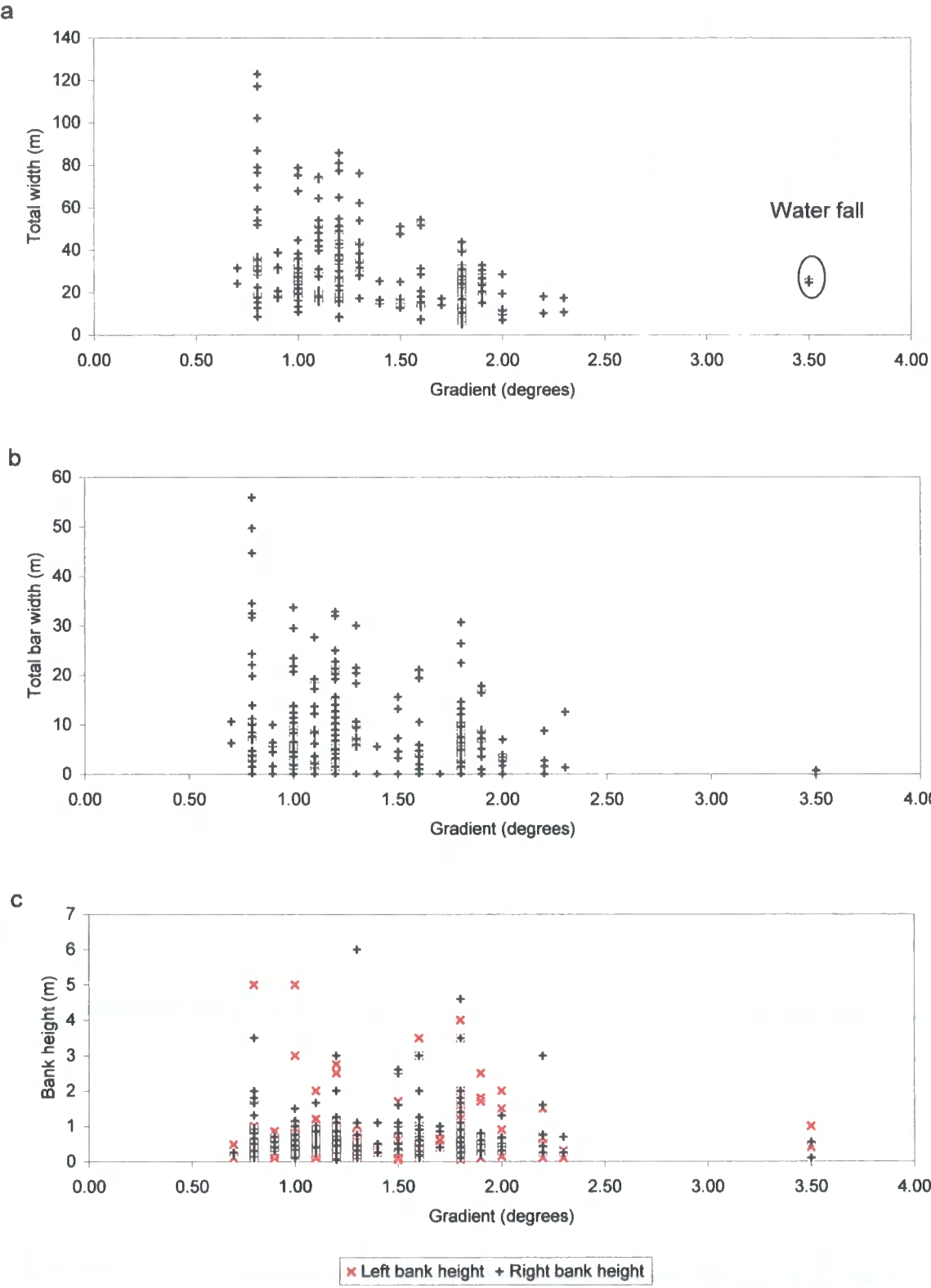
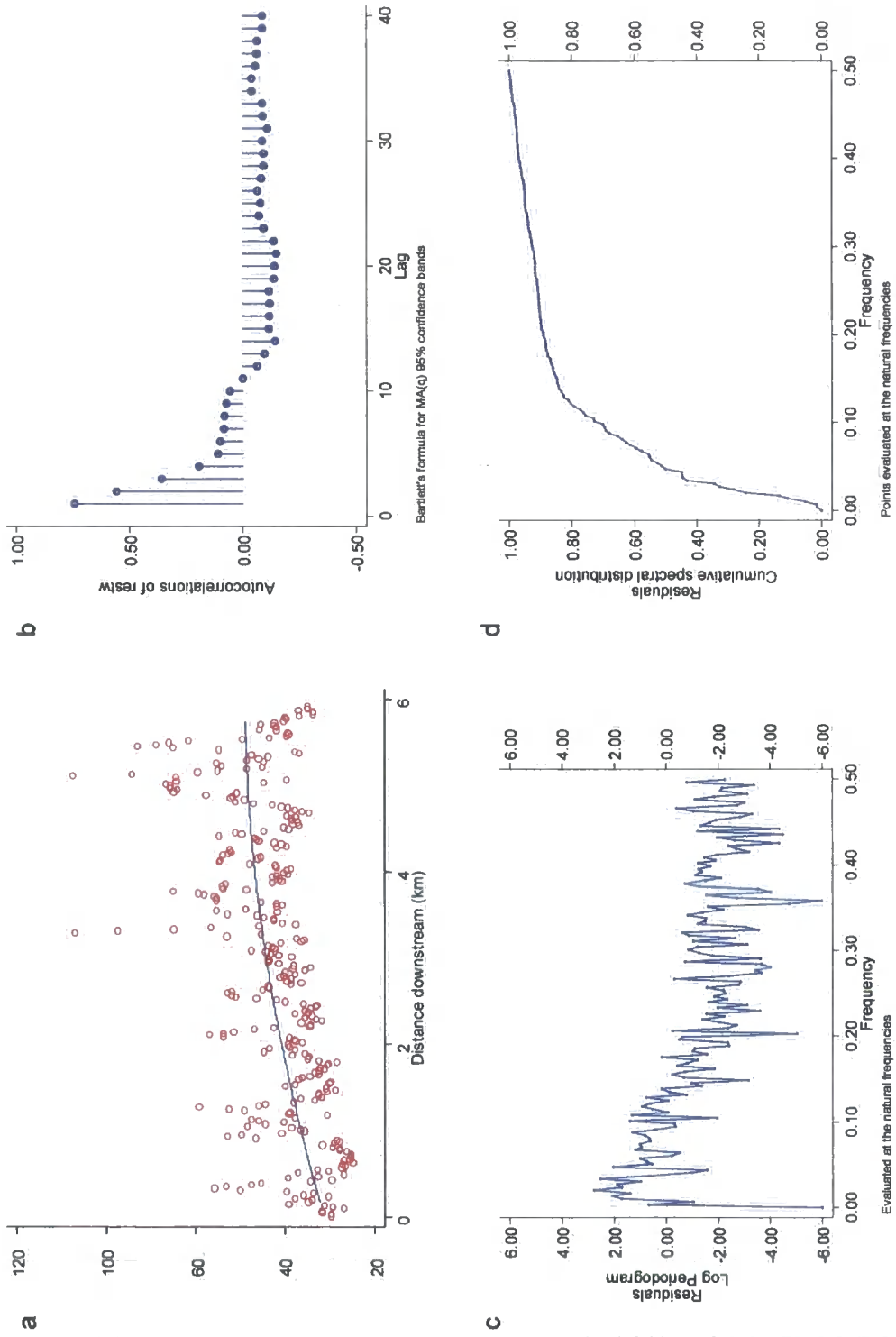


Figure 7.6 Time series analysis of total channel width along Trout Beck and the River Tees: (a) de-trending using Quadratic Regression, (b) Auto Correlation, (c) Spectral Density Function and (d) Cumulative Spectral Density Function.



(Figure 7.6c). Generally, as the frequency of variations in the channel width increases the amount of variability in the channel width declines. However, at frequencies of around 0.20 the amount of variation in channel width becomes stable, indicating that beyond this, increasing frequencies of changes in channel width do not show any further decline in magnitude. This indicates the frequent alternations in channel width occur with a similar magnitude across a range of total channel widths. The cumulative spectral distribution illustrates the importance of wide reaches. Three notable jumps occur in the cumulative curve, indicating the presence of three particularly wide reaches. These wide reaches can be seen in the total channel width data (Figure 7.2a).

7.2.2 Comparisons between the River Tees and River Wear

The total channel width structure of the upper Teesdale study reach appears to be very similar to the total channel width of the River Wear during 1951, with alternations between spatially persistent wide and narrow reaches (Figure 5.8a). However, active gravel bars were more significant along the River Wear during 1951 (higher ratio of exposed bar to wetted channel) than along the River Tees (Figure 7.2c), which has a ratio similar to that of the Wear during 1991 (Figure 5.12c). The similarity in channel structure between the Wear in 1991 and the contemporary Tees channel is highlighted by a comparison of summary width statistics for the Rivers Wear and Tees (Table 7.1) The mean width of the Tees is similar to that of the Wear in 1991. However the standard deviation of width (which indicates variation about the mean and gives an indicator of variation in width) for the Tees falls between that of the Wear in 1951 and 1991. This reflects the presence of wide reaches along the Tees, but indicates these are less significant than those present along the Wear in 1951. The similar planform structure of the Tees is smaller than that of the Wear in 1991, albeit with some locally wide reaches. Both are characterised by historically low rates of sedimentation, with the exception of the Trout Beck reaches.

Table 7.1 Comparison of channel width series summary statistics for the River Wear and River Tees.

River	Wear				Tees
	1856	1896	1951	1991	2002
Number of measurements	621	621	621	621	296
Total width (m)	28627	28081	22197	12634	6718
Mean width (m)	46.10	45.22	35.74	20.35	22.7
Standard deviation	31.97	31.47	25.51	6.42	10.49

Comparing the time series analysis results provides a more rigorous comparison. The autocorrelations for the Wear and Tees reaches appear to support the assertion that the Tees reach represents a transitional form between the Wear in 1951 and 1991 (Figure 7.7). The Tees reach shows a comparatively low persistence in channel width, reflecting a lack of persistence in wide and narrow sections along the Tees reach. The wide sections of the Tees reach, in particular, are significantly less persistent. The spectral density functions provide strong evidence that the Tees reach falls in a transition between the Wear in 1951 and 1991 (Figure 7.8). The variation in channel width has a notable flattening out at a frequency of 0.20. The Tees shows a smaller magnitude in difference between wide and narrow reaches than the Wear (1856-1951). At low frequencies the channel width structure is comparable to that of the River Wear in 1951, indicating a low frequency oscillation between relatively wide (sedimentation zones) and narrow intervening reaches. However at frequencies beyond 0.20 the series is more akin to the Wear in 1991 with changes in channel width being of a similar magnitude. This result indicates that as the Tees reach retains some wide reaches at low frequencies the channel shows considerable width variation, but the relatively limited persistence of these has resulted in a trend towards lower variations in channel width at high frequencies of width variation. This trend is also apparent from the cumulative spectral density functions (Figure 7.9) that confirm the Tees structure is transitional between the Wear in 1951 and 1991.

Figure 7.7 Autocorrelations of de-trended total width for the River Wear in (a) 1856, (b) 1896, (c) 1951 and (d) 1991 and River Tees in (e) 2002.

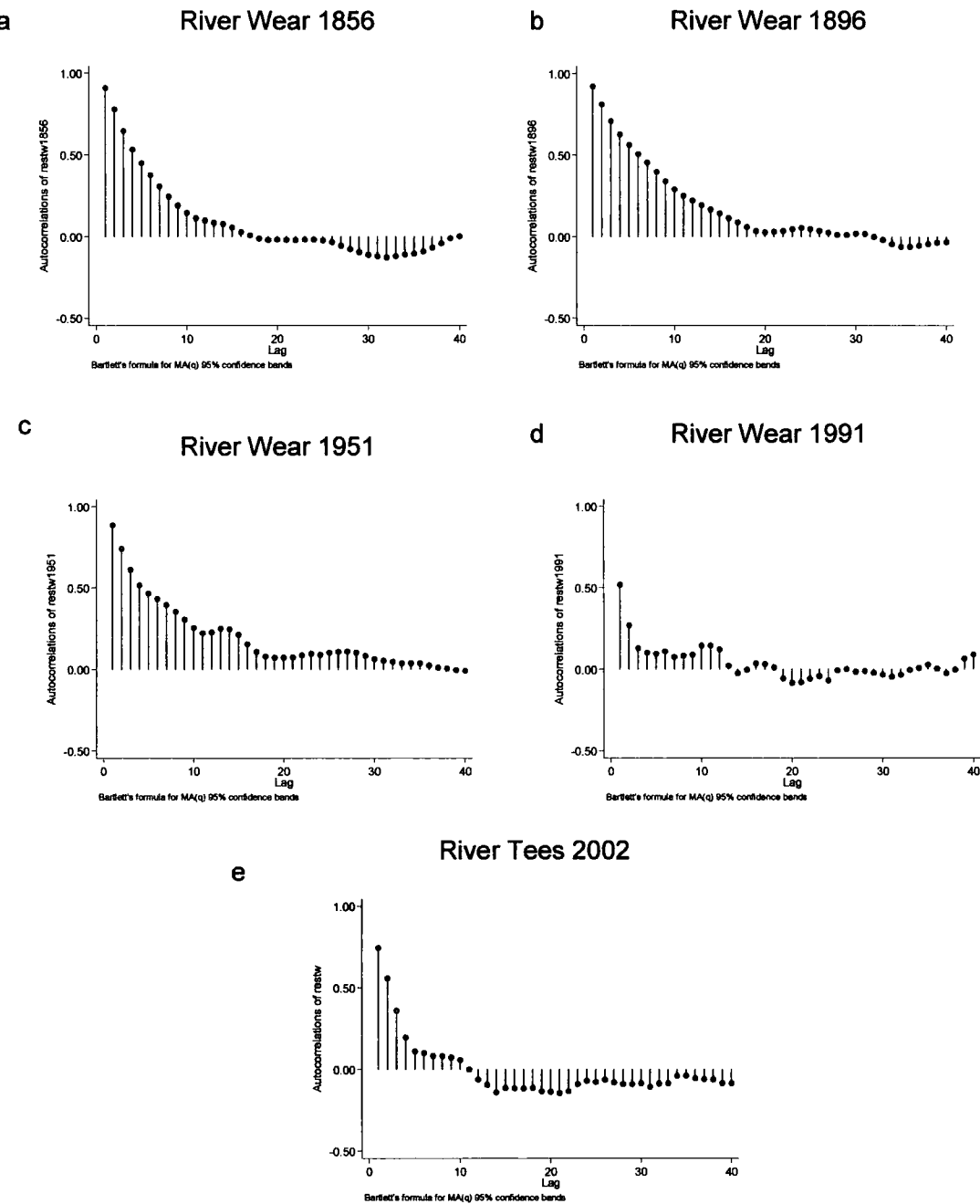


Figure 7.8 Spectral Density Function of de-trended total width for the River Wear in (a) 1856, (b) 1896, (c) 1951 and (d) 1991 and River Tees in (e) 2002.

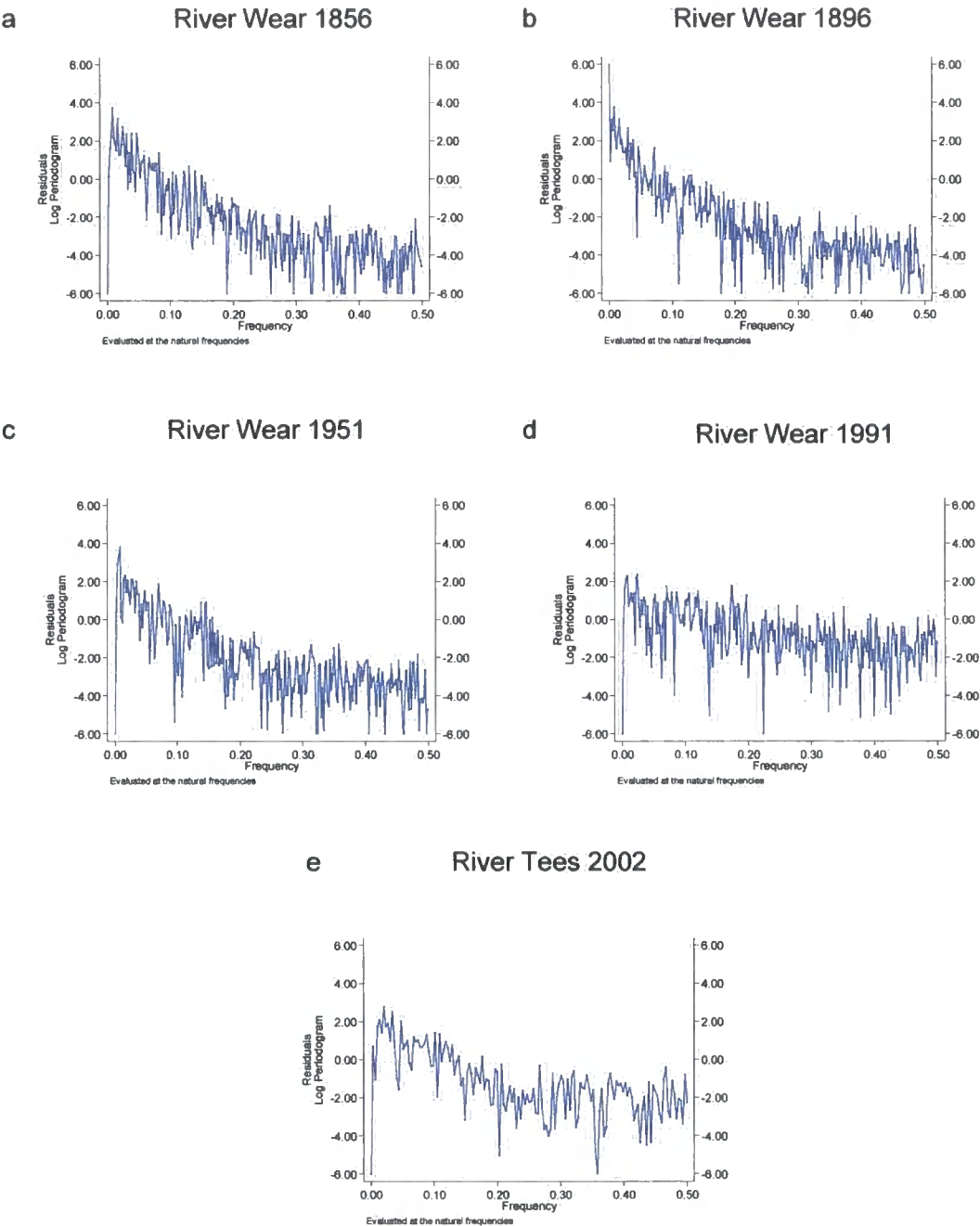
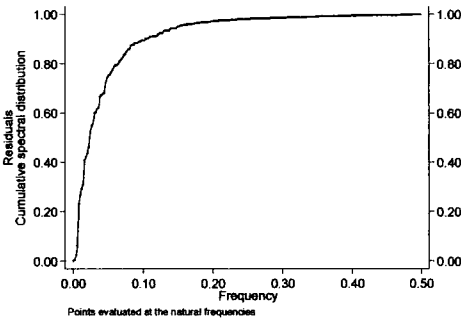
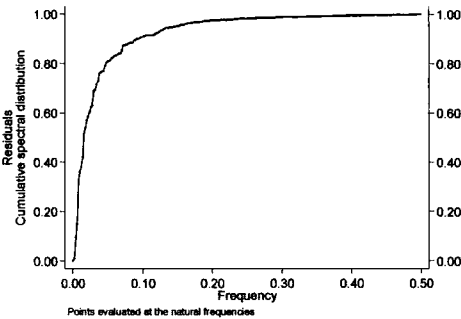


Figure 7.9 Cumulative Spectral Density Function of de-trended total width for the River Wear in (a) 1856, (b) 1896, (c) 1951 and (d) 1991 and River Tees in (e) 2002.

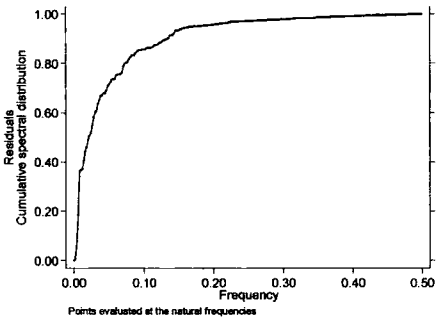
a River Wear 1856



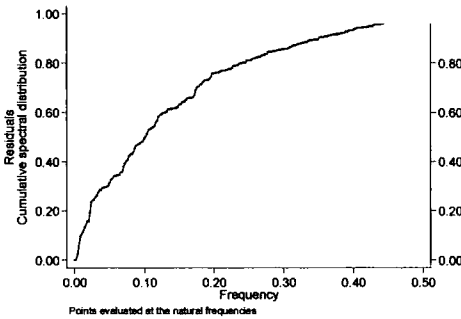
b River Wear 1896



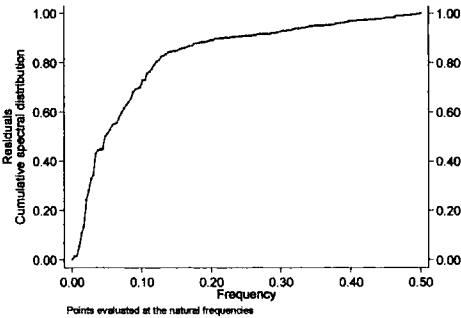
c River Wear 1951



d River Wear 1991



e River Tees 2002



7.3. Reach-scale investigations into historic channel planform change

7.3.1. Study reach characteristics

Four reaches showing evidence of historical and contemporary channel planform change have been identified along the upper Teesdale channels (Figure 3.12). Two of these reaches are located along Trout Beck and the remaining two are located along the River Tees. Detailed examinations of these reaches were made in an attempt to determine the cause of channel changes. In addition, the distribution of these reaches within the catchment allowed sediment transfers to be identified. The characteristics of these study reaches are summarised in Table 7.2. The following sections describe the history of channel change in these reaches, the cause of which is considered in a latter section of the chapter.

Table 7.2 Table showing the characteristics of each of the study reaches examined.

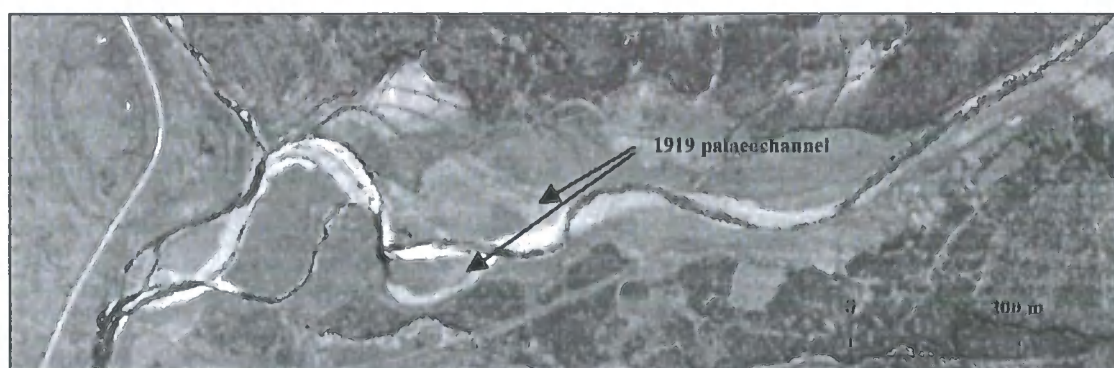
Reach	Height (m)		Length (km)	Slope	Stream order	Upstream catchment area (km ²)
	Upper	Lower				
Trout Beck Ford	565	551	0.550	0.025	3	7.00
Trout Beck Netherhearth Foot	549	539	0.500	0.020	3	7.26
Crookburn Foot	535	516	1.300	0.007	4	34.70
High Crag Foot	513	508	0.900	0.005	4	37.60

7.3.2 Methodological considerations

Reconstructions of channel planform in Weardale (Chapter 6) were generated using the GIS software ArcView. This enabled changes in channel planform, in particular gravel area, to be quantified. However this technique requires archival sources to be geo-referenced (discussed in chapter 3), which demands a series of control points with known national grid co-ordinates located close to the river channel. Unfortunately the remote location of the upper Tees study reaches meant that insufficient control points (buildings for example) were available to enable accurate geo-referencing. As an alternative the software Freehand was used as this enables

easy planform derivation and resizing from maps and aerial photograph sources in the absence of geo-referencing. However Freehand does not enable features to be measured with accuracy and as a result gravel bar areas could not be measured reliably. One significant advantage of Freehand is the flexibility this graphics package provides. In a number of instances the early maps were found to be rather generalised so channel planform reconstruction was based on a combination of both archival map analysis and aerial photograph analysis. Aerial photographs allowed palaeochannels to be used to accurately locate the position of the river channel and associated gravel bars. For example, along the Trout Beck Netherhearth reach the position of the river channel during 1919 could be reconstructed by comparing an historic map of the reach with the aerial photograph (Figure 7.10). Generally the palaeochannels agreed extremely well with the historic maps allowing changes in the location of the active channel to be determined with accuracy.

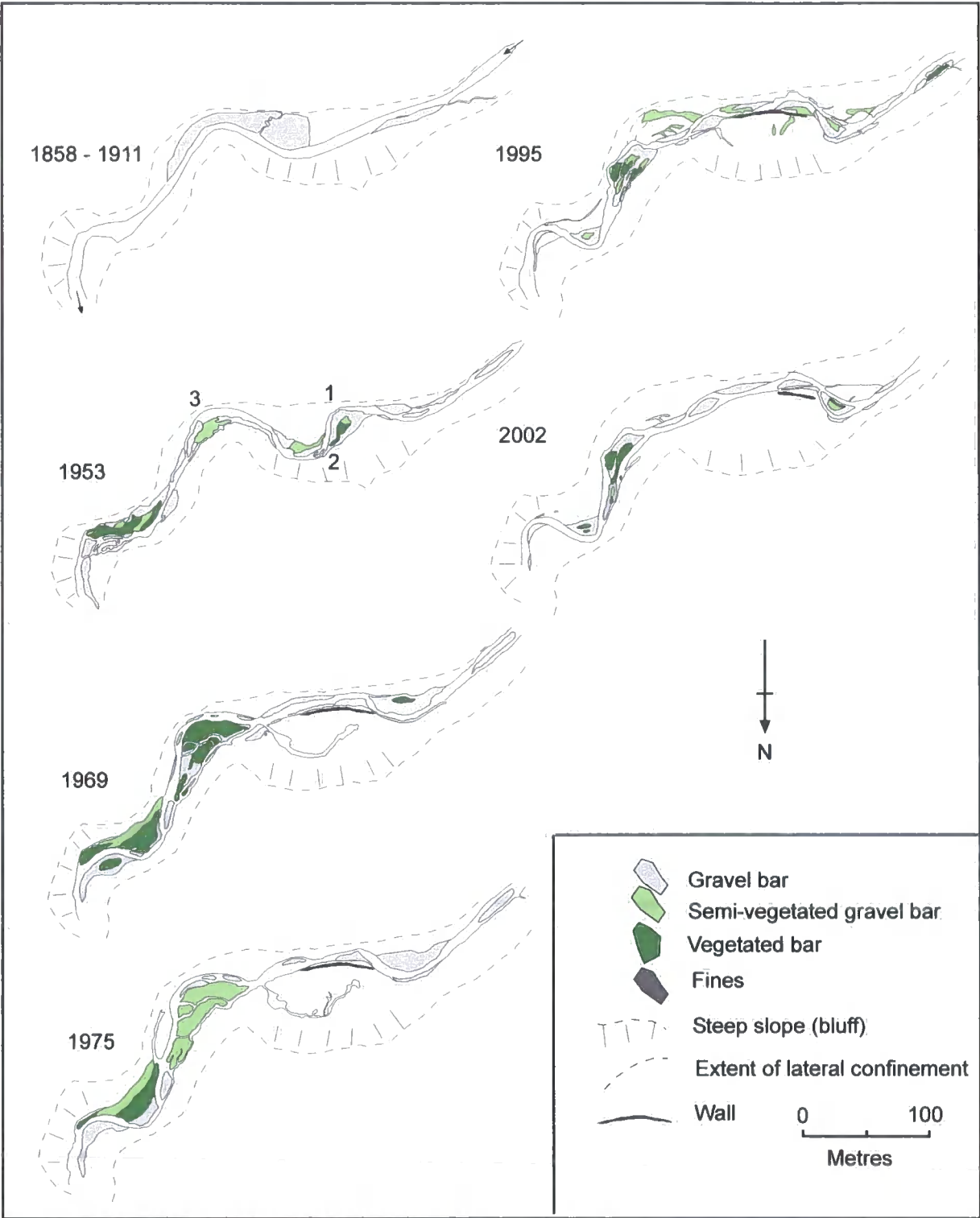
Figure 7.10 Aerial photograph of the Trout Beck Netherhearth reach taken in 1953 on which the 1919 palaeochannel is visible; such detail provided important additional information for the planform reconstructions. Source: MOD RAF aerial photography.



7.3.3 Trout Beck Ford

Over the period 1858 to 1911 the reach was characterised by a stable single thread channel dominated by a large lateral bar on the right bank across which a minor tributary channel flowed (Figure 7.11). Between 1911 and 1953 a reduction in the extent of active gravel along the southern bank occurred and was coincident with an increase in the distribution of gravel within the reach. Planform changes associated with this change involved the development of new bends in location 1 and

Figure 7.11 Channel planform changes along the Trout Beck Ford study reach 1858 - 1995
Numbers indicate locations referred to in the text.



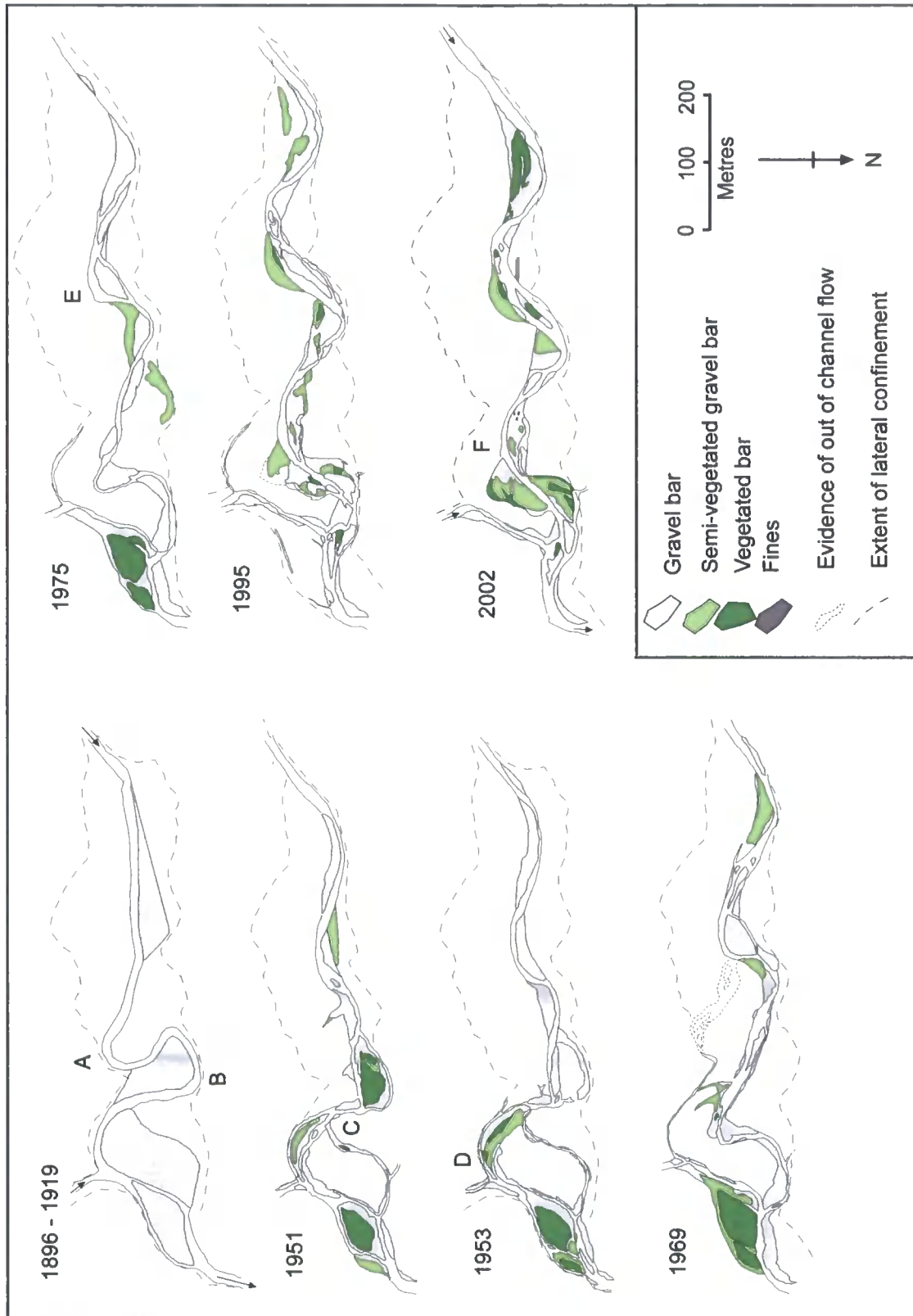
2. In location 3 the bend migrated across its right bank bar until lateral confinement prevented further development. The large right bank bar between locations 1 and 3 was completely vegetated, perhaps due to a decrease in sediment delivery to the reach. In the lower portion of the reach localised sedimentation led to the development of numerous medial bars. Sedimentation may have been related to sediment delivery from bank erosion associated with the bend enlargement in the centre of the reach.

Channel changes continued between 1953 and 1969. In the lower section of the reach the medial bars were removed and the channel now dissects their former location (Figure 7.12). The bend in the centre of the reach was cut-off, lingering as a long backwater. Immediately downstream of the former bend, channel division developed through the formation of a secondary channel across the neck of bend 3; mid-way across the bend this channel divided into two branches before rejoining the main channel. The development of gravel bars in the bend sedimentation may have encouraged this out of channel flow. Between 1969 and 1975 the channel planform of the reach remained largely unchanged. The active bars surrounding the secondary channels began to vegetate, although complete vegetation cover in the core of the bend was replaced by semi-vegetated gravel. By 1995 the flow had switched from the original bend to the secondary channels, which widened in response. As a result the original bend was completely abandoned and began to vegetate. Only minor changes in the organisation of gravel bars occurred between 1995 and 2002. Generally a gradual decline in the extent of active gravel occurred along the reach between 1953 and 2002.

7.3.4 Trout Beck Netherhearth Foot

Between 1896 and 1919 the reach was dominated by a single thread channel with large lateral gravel bars, channel division occurring only downstream of the confluence of Netherhearth Burn. Between 1919 and 1951 bend A was completely cut-off and vegetated (Figure 7.12). The bend in location B was also by-passed although it remained active in 1951 as a secondary channel before becoming abandoned altogether by 1953. A particularly significant change was the development of a new channel in location C, which followed the margin of the large gravel bar active between 1896 and 1919. Initially this channel was only active during

Figure 7.12 Channel planform changes along the Trout Beck Netherhearth Foot reach 1896 - 1995
 Letters indicate locations referred to in the text.



high flow events, but became permanently occupied by 1953. Despite some re-organisation of gravel bars the period 1919-1953 saw a significant decline in the extent of active gravel in the reach.

Between 1953 and 1969 the large bend in location D was completely abandoned, the main flow becoming routed via the chute channel of the early 1950s (Figure 7.12). This channel widened in response and several lateral bars formed, promoting a tightening of the bends along this reach. Channel division ceased downstream of the Netherhearth confluence and the medial bars became vegetated. This is likely to have been caused by the abandonment of bend F diverting the flow of Trout Beck away from this reach. The 1969 aerial photograph of the reach indicated a recent out of channel flow event had occupied the 1919 palaeochannel, with a clear contrast in the wetness of the floodplain and areas of localised standing water. The flow during this event also appears to have been routed into the palaeochannel of bend D. Between 1969 and 1975 the channel planform remained essentially unchanged (Figure 7.12). The period 1953 –1975 was associated with relatively little change in the extent of active gravel within the reach.

Several changes occurred between 1975 and 1995 and were associated with an increase in the extent of gravel bars and related shifts in the thalweg. In location E a reduction in bend curvature and downstream channel widening occurred in response to the elongation of the mid-channel bar. Channel migration occurred at location F, which, coupled with the bypassing of the bends immediately downstream, resulted in the development of a single large bend. This appears to have promoted deposition downstream where medial bars developed at the confluence of Netherhearth Burn. Overall, this period was characterised by an increase in the complexity of gravel bars, particularly an increase in the extent of medial bars. Channel changes between 1995 and early 2002 were restricted to localised re-working of gravel bars, such as bar coalescence at the confluence of Netherhearth Burn. Generally this period of planform stability was marked by continued vegetation colonisation of gravel bars within the reach.

7.3.5 Crookburn Foot, River Tees

Archive maps were available for the period 1858 – 1919 and although bar depiction on these maps is generalised, they provide good evidence of the channel planform over this period. Broadly speaking the planform that characterises the reach today was established prior to 1858, although numerous changes to the position of the wetted channel within the channel belt have occurred. According to the archive maps the channel planform remained unchanged between 1858 and 1896 and the only change that occurred from 1896 to 1919 was the formation of a secondary channel in location 1, although this change may represent stage difference between surveys (Figure 7.13).

The most significant channel changes along this reach were restricted to the central sections of the reach. Following a period of apparent inactivity between 1858 and 1919, sedimentation and associated channel changes occurred between 1919 and 1953. Deposition within the channel both to the left and right of the vegetated medial bar caused the majority of flow to switch through the centre of the channel belt. The formation of the large active bars in this area by 1953 suggests an increase in the rate of sedimentation within the channel. By 1975 the wetted channel switched locations again, dividing and flowing along the left and right banks with a large mid-channel bar developing in the location of the 1953 channel alignment. The channel alignment adopted in 1975 remained largely the same in 1995, although bank erosion along the right bank resulted in the formation of a new mid-channel bar (Figure 7.14). At present the dry channel evident in Figure 7.14 is only activated at high flow stage and based on 1919 map evidence it appears this channel was last permanently occupied by flow during the early twentieth century. Generally the period 1953-1995 was characterised by a decline in the extent of active gravel within the reach due to vegetation colonisation of gravel bar surfaces.

Figure 7.13 Channel planform changes along the Crookburn Foot reach 1858 - 1995

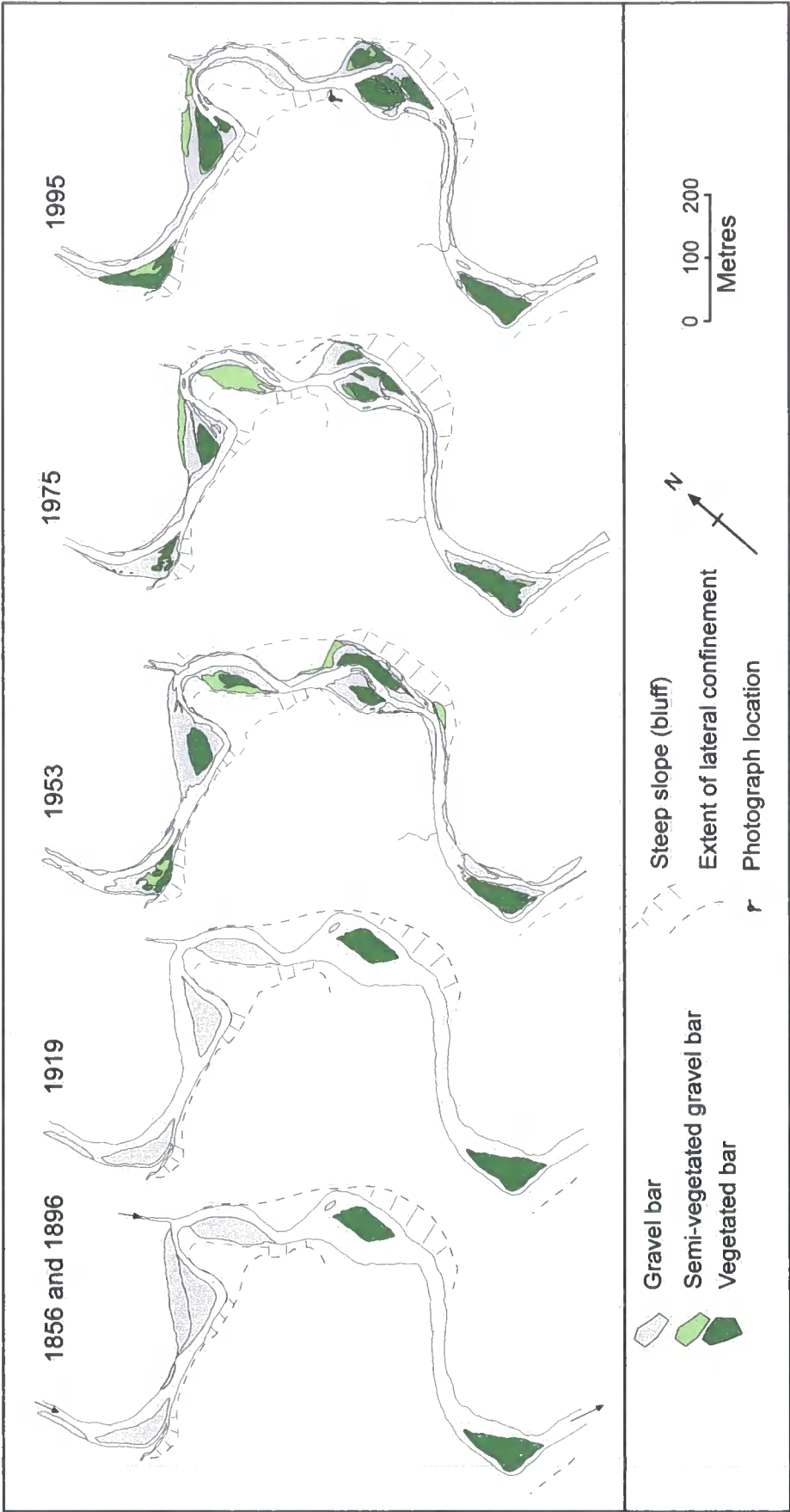


Figure 7.14 Photograph showing the central portion of the Crookburn Foot reach, taken from the right bank during 2002 (see Figure 7.13 1995 map for location). Flow is from left to right and the dates of visible palaeochannels are indicated. The 1919 channel is occupied during high flow and acts as a flood channel.



7.3.6 High Crag Foot, River Tees.

In 1858 this reach was characterised by a predominantly single thread channel with a single medial bar in the lower portion of the reach (Figure 7.15). With the exception of localised vegetation colonisation and gravel accretion onto the tail of the bar, channel changes along this reach were restricted to the upper and middle portion of the reach. In the upper portion of the reach, sedimentation within the channel between 1911 and 1953 led to the formation of a large medial gravel bar and a number of lateral bars. By 1953 the latter had become incorporated into the channel as medial bars. By 1995 the upper medial bars had become attached to the right bank once more, but with secondary channels conveying flow during high stage. Vegetation colonisation occurred where these bars remain exposed at high stage.

In the middle of the reach, erosion of the right bank progressed as the left bank bar was enlarged between 1858 and 1896. Following a period of relatively little change between 1896 and 1911, bank erosion resumed between 1911 and 1953. Erosion in this location led to bank recession towards the lower reaches of Little Dodgen Pot Sike. Continued bank erosion in the middle of the reach resulted in the capture of the lower section of the Little Dodgen Pot channel between 1953 and 1975. As a result, in 1975 the main flow of the River Tees was divided between the original channel and the former Little Dodgen Pot channel, which widened in response (Figure 7.16).

Figure 7.15 Channel planform changes along the High Crag Foot reach 1858 - 1995

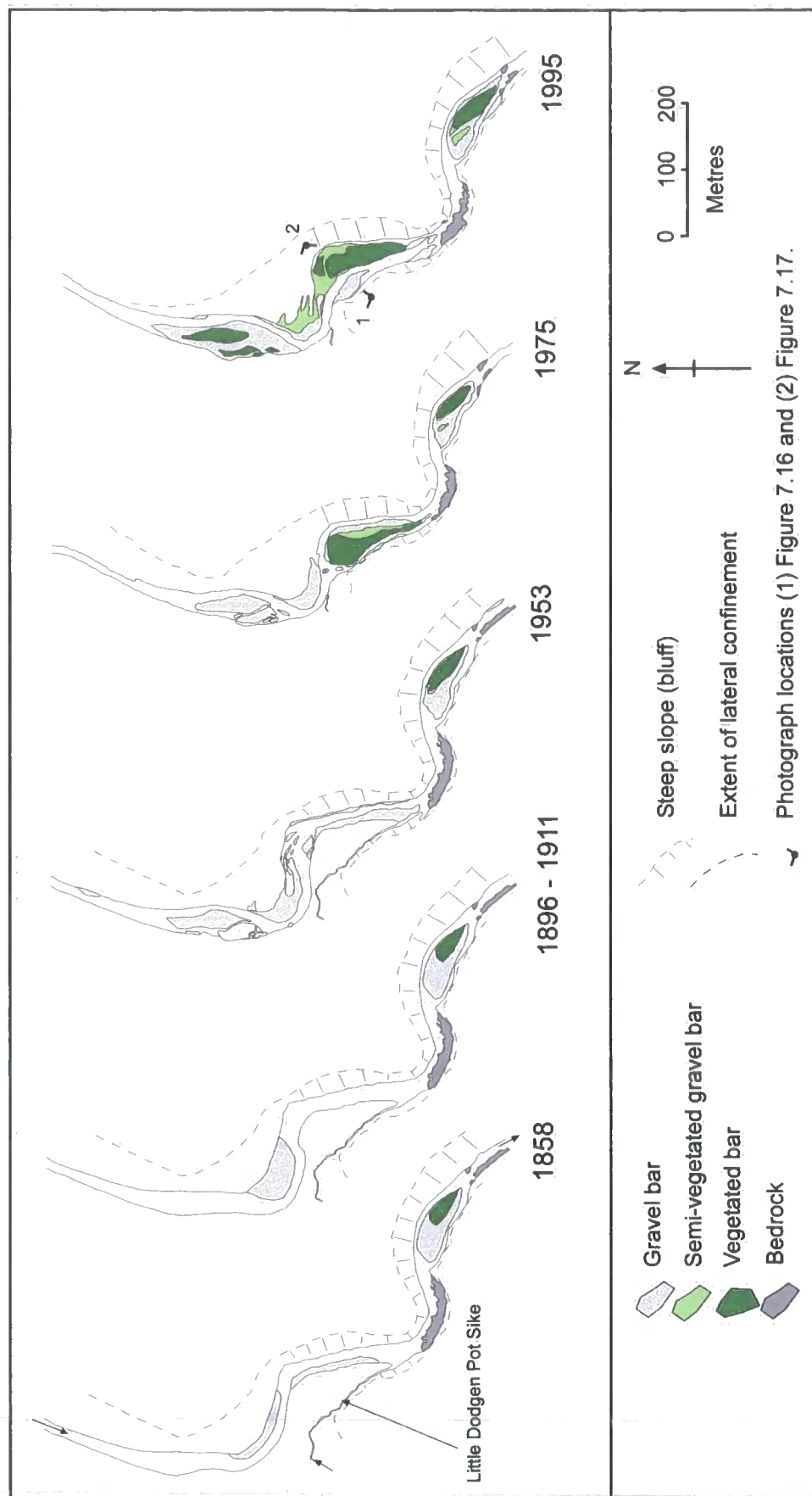


Figure 7.16 View of the middle bend of the High Crag Foot Reach looking upstream. The former location of Little Dodgen Pot can be seen in the foreground.



By 1995 the former channel of Little Dodgen Pot had enlarged to convey all the normal flow of the Tees; the original channel becoming abandoned (Figure 7.17). At the entrance to this former channel, vegetation colonisation of the bars occurred (Figure 7.17). This suggests that unlike the secondary channels upstream the former bend does not convey flow at high stage. This is because sedimentation occurred in the entrance to the former channel preventing flow entering the reach. Additionally, the new channel has a higher channel gradient which enabled channel enlargement to a size sufficient to convey the normal flow of the river. Aerial photograph evidence from the upper catchment of the River Tees above the Trout Beck confluences provided two additional examples of this form of planform change.

Figure 7.17 Entrance to the former channel of the River Tees at High Crag Foot, the current wetted channel occupies the former location of Little Dodgen Pot Sike. Note the recent sedimentation in the entrance to the former bend.



7.3.7 Summary

The changes in gravel bar area over the study period for each reach are summarised in Table 7.3. Generally study reaches were stable during the late nineteenth century and early twentieth century. However, the period 1911 to 1953 saw the onset of significant changes in channel planform associated with the re-organisation of gravel bars and movement of the wetted channel. In the upper catchment this period was associated with a decline in the extent of gravel bars, while in the lower catchment an increase in bar extent occurred. The divide between decreases in gravel area in the upper catchment and increases in the lower catchment lies in the middle of the Crookburn Foot reach. This contrast between the upper and lower catchment may represent the movement of sediment through the catchment. From 1953 onwards channel planform changes continued as gravel bars and the position of the wetted channel were re-organised. This period was also characterised by a decline in the extent of gravel bars due to the gradual colonisation of bar surfaces by vegetation. The potential causes of these changes in channel planform are considered in section 7.5.

Table 7.3 Summary of changes in the extent of gravel bars within the study reaches over the period 1858-1995, subdivided into five time intervals. Symbols indicate direction of change (red symbols indicates change greater than half the total gravel area of the reach, black symbols indicate change less than half).

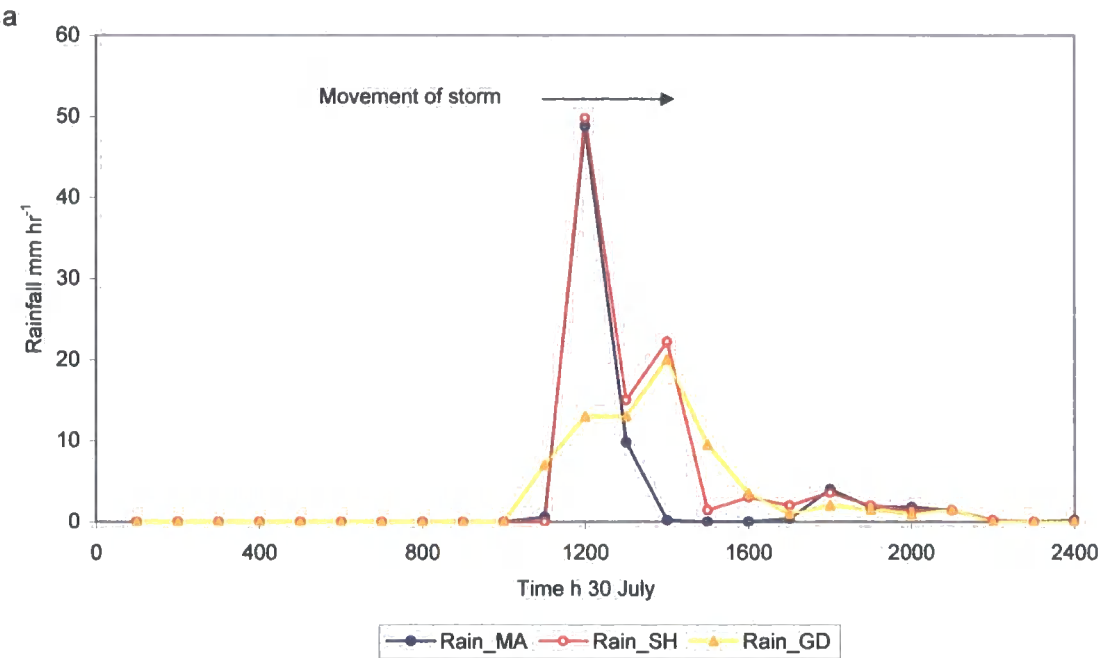
Reach	1858-1896	1896-1911	1911-1953		1953-1975	1975-1995
Trout Beck Ford	No change	No change	—		—	—
Netherhearth Foot	No data	No change	—		—	—
			Upper	Lower		
Crookburn Foot	No data	No change	—	+	—	—
High Crag Foot	No change	No change	+		+	—

7.4 The impact of a high magnitude flood event on channel planform.

7.4.1 The 30th July 2002 event.

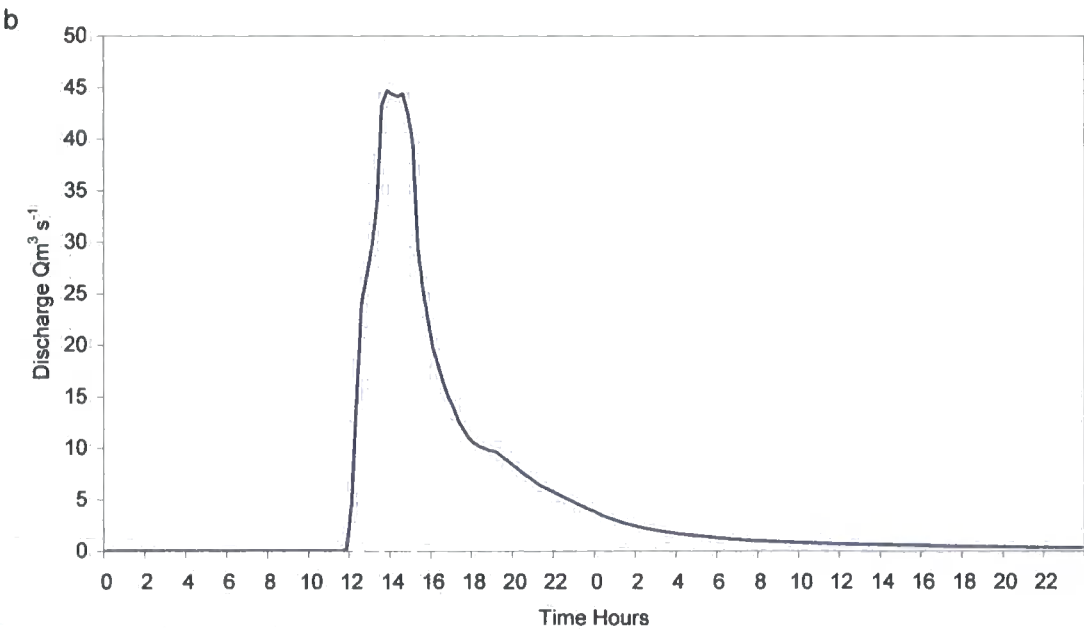
An intense convective storm cell passed over the upper Tees catchment on the 30th July 2002. Rain began to fall between 10 and 11am on Great Dunn Fell (Figure 7.18 a). The storm intensified as it moved in a north-westerly direction, with extremely high intensity rainfall occurring between 11:00 and 12:00, peaking at 50 mm hr⁻¹ over the lower reaches of Trout Beck (Figure 7.18 MA and SH). This rainfall was of such intensity that within two hours the discharge of Trout Beck rose from low flow conditions to an exceptional discharge of approximately 45 m³ s⁻¹ by around 14:00 (Figure 7.18b). At its peak the flow by-passed the weir over the left bank of the channel so this peak discharge is under representative of the maximum flow, which may have been as high as 48 m³ s⁻¹. The peak discharge was prolonged due to an increase in rainfall intensity over nearby Shaft Hill at 14:00 as the storm moved across the catchment (Figure 7.18a). Although discharge initially declined rapidly following peak flow, very high discharge continued into the early hours of the

Figure 7.18 Charts showing (a) rainfall in upper Teesdale and (b) discharge data for Trout Beck on the 30/31 July 2002 in upper Teesdale. For locations see Figure 3.12.



Locations of rain gauges:

MA = Moor House Automated weather station in met area next to field lab
 SH = Shaft Hill, Automated weather station on Tees Stage Station
 GD = Great Dun Fell, Automated weather station next to Radar Station



following morning (Figure 7.18b). The following statistics enable an appreciation of the truly exceptional nature of this event. High discharge flood events in this catchment tend to occur in the winter months, particularly February, due to snow melt events. During February 1997, for example, the largest flood recorded peaked at around $15 \text{ m}^3 \text{ s}^{-1}$ (Warburton, 1998 p 10). Storm events following the relatively dry summer of 1995 showed peak discharges of 4 to $5 \text{ m}^3 \text{ sec}^{-1}$ (Warburton and Demir, 1998). Generally, in the Trout Beck catchment flow exceeds $0.5 \text{ m}^3 \text{ s}^{-1}$ 29% of the time (Burt et al., 1998).

A field-based assessment of the distribution of the geomorphological impacts of the flood revealed a close correspondence to the movement of the storm cell. The upper half of the catchment (Trout Beck and Upper Tees catchments) was affected to a greater extent than the lower, and flood impacts on the river channel were greater in the Trout Beck catchment than the upper Tees catchment. While significant channel changes occurred in the upper catchment, involving both bed and bank erosion and deposition within and beyond the channel, there were no significant changes to the river channel downstream of the Trout Beck-Tees confluence. The only impact was some small scale and highly localised bar re-working. The contrasts in the response was primarily a consequence of the location of the storm cell in the upper reaches of the catchment and its north westerly migration. Evidence of flood damage in the upper reaches of the South Tyne catchment (Tynehead) attest to this. Overall the most significant channel modifications occurred along the Trout Beck Ford and Trout Beck Netherhearth Foot reaches, because these were located close to the greatest storm intensity (close to the Main and Shaft Hill weather stations, Figure 7.18).

7.4.2. Trout Beck Ford Reach

Field observations made the day after the flood event indicated that the majority of the floodwaters were routed along the contemporary channel, although flow also occupied palaeochannels resulting in localised deposition of gravel spreads. The flood impacts along the active channel were principally associated with deposition of large quantities of coarse sediment over the entire length of the reach (Figure 7.19). The medial bar located in the upper bend was almost completely covered by fresh gravel and the right-hand channel was completely infilled (Figure 7.20). Flow is now routed along the left bank of the bend. In the middle section of the reach deposition

Figure 7.19 Trout Beck Ford reach (a) immediately prior to the flood in July 2002 and (b) following the flood in August 2002. Letters indicate locations referred to in the text.

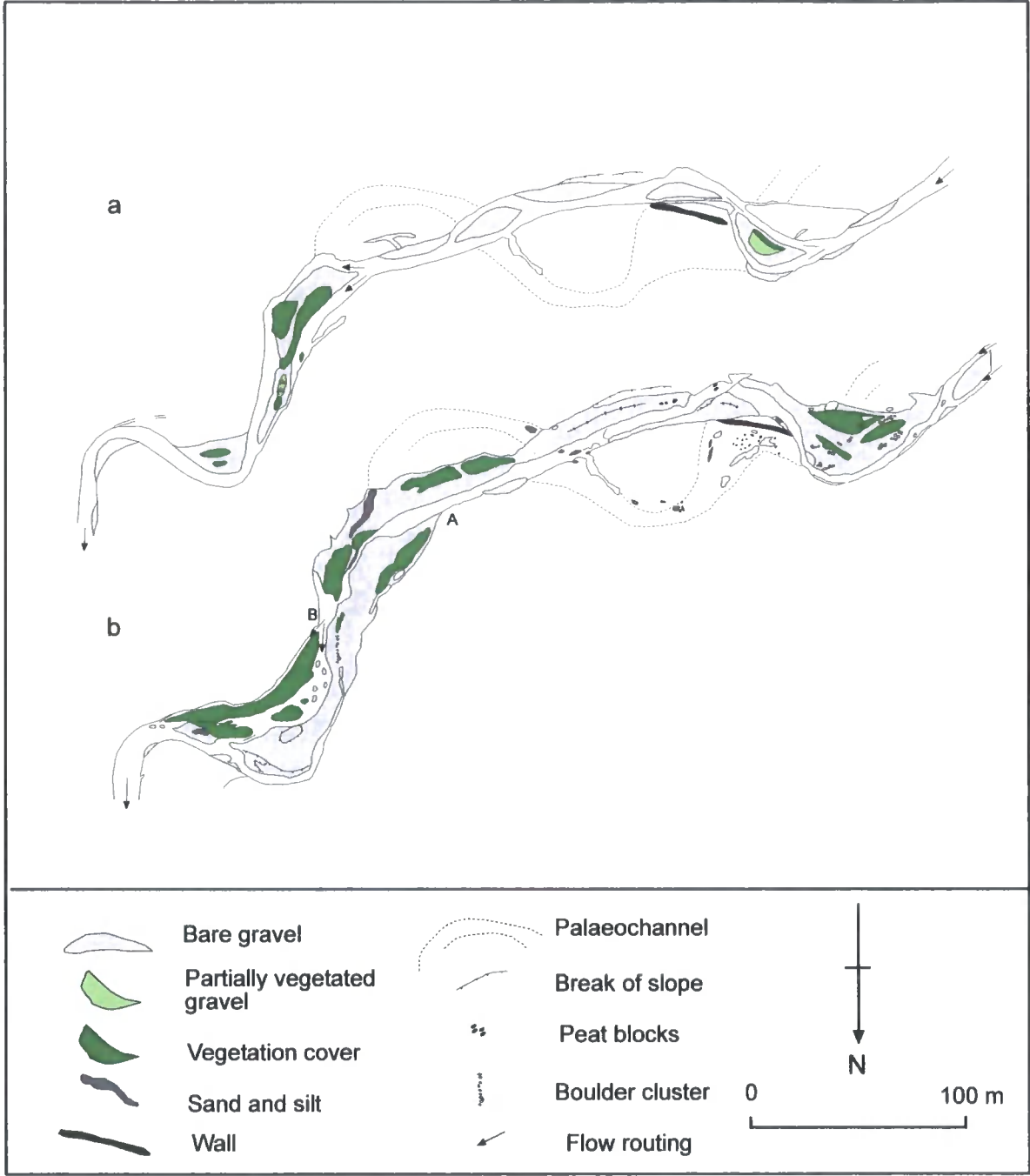


Figure 7.20 The upper bend of the Trout Beck Ford reach (a) prior to the flood in June 2002 and (b) following the flood in August 2002. Note the downstream growth of the mid channel bar upstream of the bend.

a



b



was focused along the right bank where fresh bars formed to a thickness of approximately 0.6 m, which was greater than the original channel depth, and caused overbank deposition of gravel. In location A, deposition completely blocked both channels causing the flow to become routed down the centre of this former medial bar. In location B complete blocking of the original channel caused flow to be routed over the floodplain across the bend neck. Flow also re-occupied the palaeochannel dating from 1911, forming a chute channel across the inner bend (Figure 7.21).

The significance of deposition along this reach in response to the flood is demonstrated by comparing the channel width data for this reach prior to the flood and following the flood (Figure 7.22). Active gravel has completely covered semi-vegetated and vegetated bars that were present prior to the flood. The increase in the extent of vegetated bars was caused by the formation of the chute channel in the lower portion of the reach (Figure 7.21). This chute channel resulted in the incorporation of a portion of the floodplain into the channel in this location (380-480 m downstream). As a result of the chute channel formation this has effectively become a medial bar.

Figure 7.21 View of the Trout Beck Ford reach showing flood impacts, locations referred to in the text are indicated.

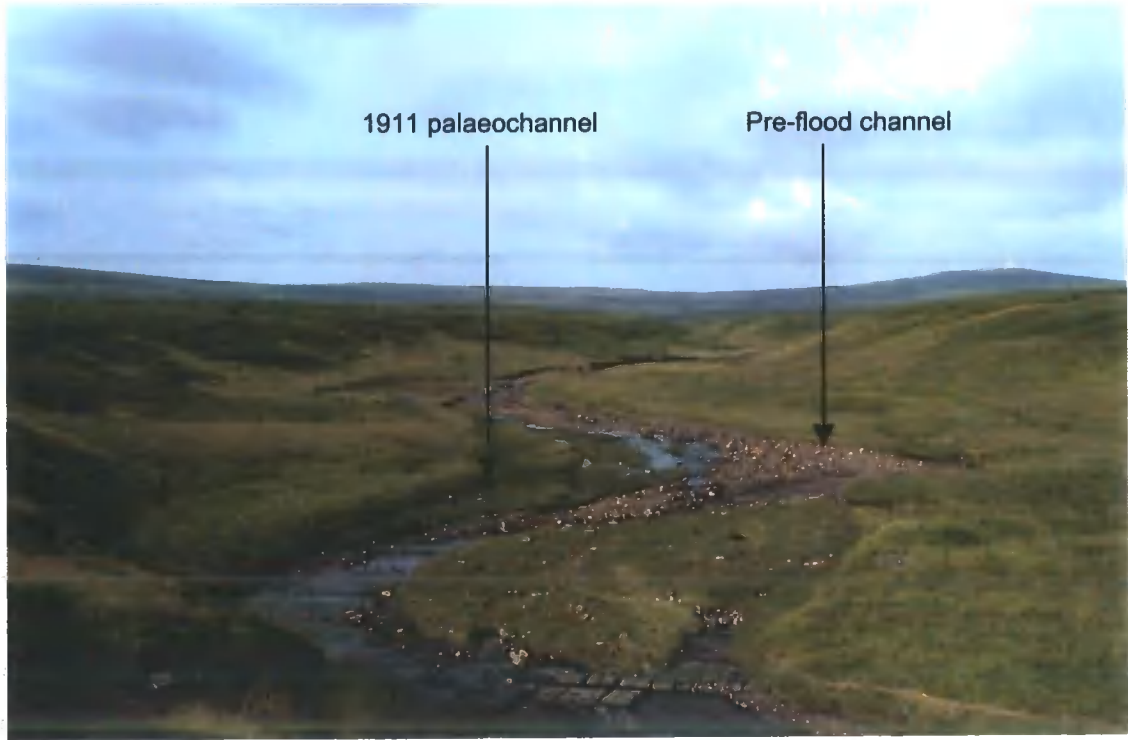
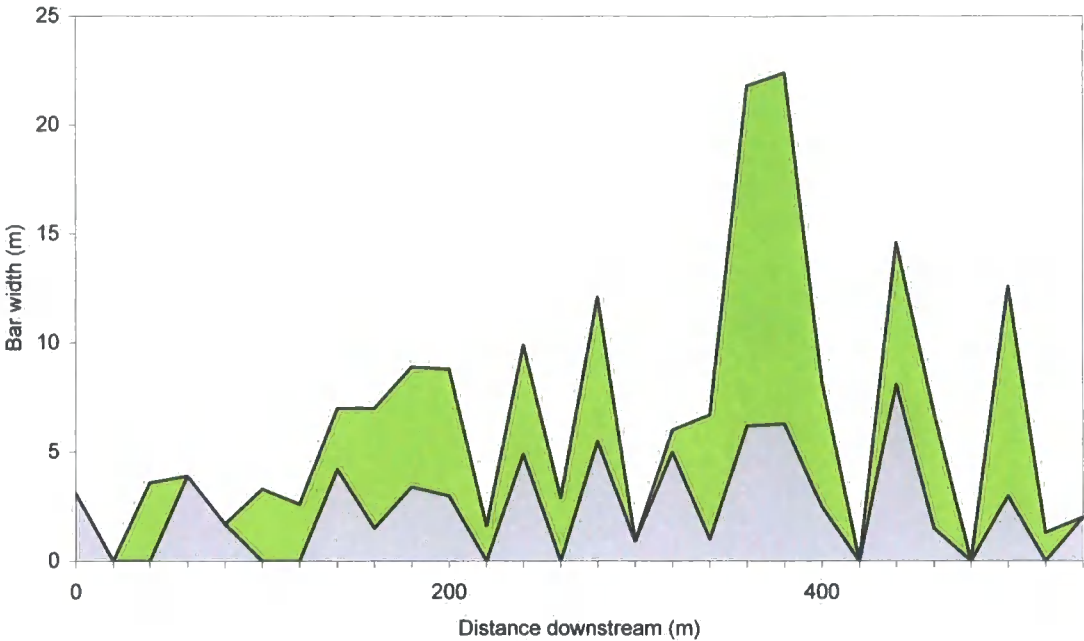
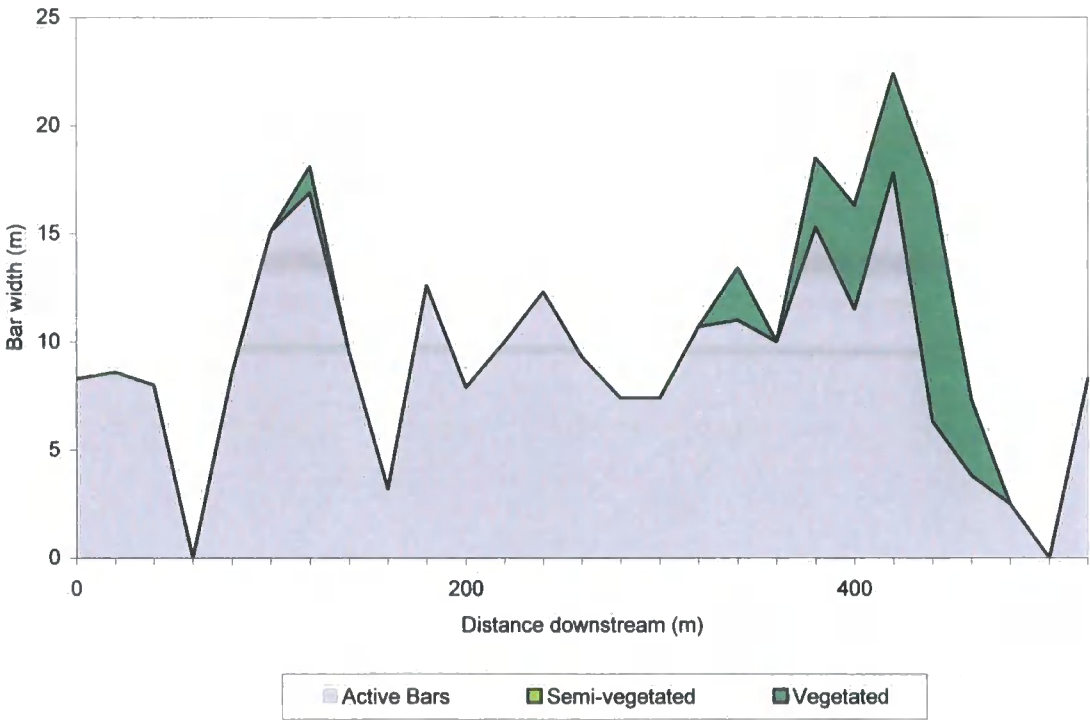


Figure 7.22 Bar widths along the Trout Beck Ford reach
(a) prior to the flood in June-July 2002 and
(b) subsequent to the flood during August 2002

a



b



7.4.3. Trout Beck Netherhearth Foot

Despite only producing relatively minor changes to the routing of the wetted channel along the reach, the flood event caused considerable bar re-working (Figure 7.23). The thalweg was locally deepened and, where the channel impinged against banks, erosion led to bank retreat (locally as much as 2 metres). Where the upper riverbank was composed of peat (location A, Figure 7.23), mass failures occurred producing several large peat blocks. The largest of these were deposited within the channel and on surrounding bars (Figure 7.24a) while the remainder were transported downstream. The majority were deposited on the gravel bar that occupies the 1969-1975 palaeochannel (location B Figure 7.23 and Figure 7.24b).

No significant channel division occurred in response to the flood and the event removed all pre-existing mid-channel gravel bars. Medial bars were lost through deposition within secondary channels and in some cases this deposition completely covered the location of bars. The main impact of the flood was a significant increase in the extent of lateral gravel bars. In several locations deposition of gravel bars increased their elevation substantially; breaks of slope depicted on Figure 7.23 indicate the locations in which this occurred. Locally, out-of-channel flow deposited spreads of gravel on the floodplain, principally in the depressions of palaeochannels. Channel changes as a result of deposition are also illustrated by comparisons of channel width data prior to and following the flood event (Figure 7.25). Substantial increases in active bar widths have occurred, principally at the expense of semi-vegetated and vegetated bar surfaces that were covered with fresh spreads of gravel. Locally bank erosion occurred, and was concentrated at a point 260 m downstream from the top of the reach (Figure 7.25).

Figure 7.23 Trout Beck Netherhearth Foot reach (a) immediately prior to the flood in July 2002 and (b) following the flood in August 2002. Letters indicate locations referred to in the text.

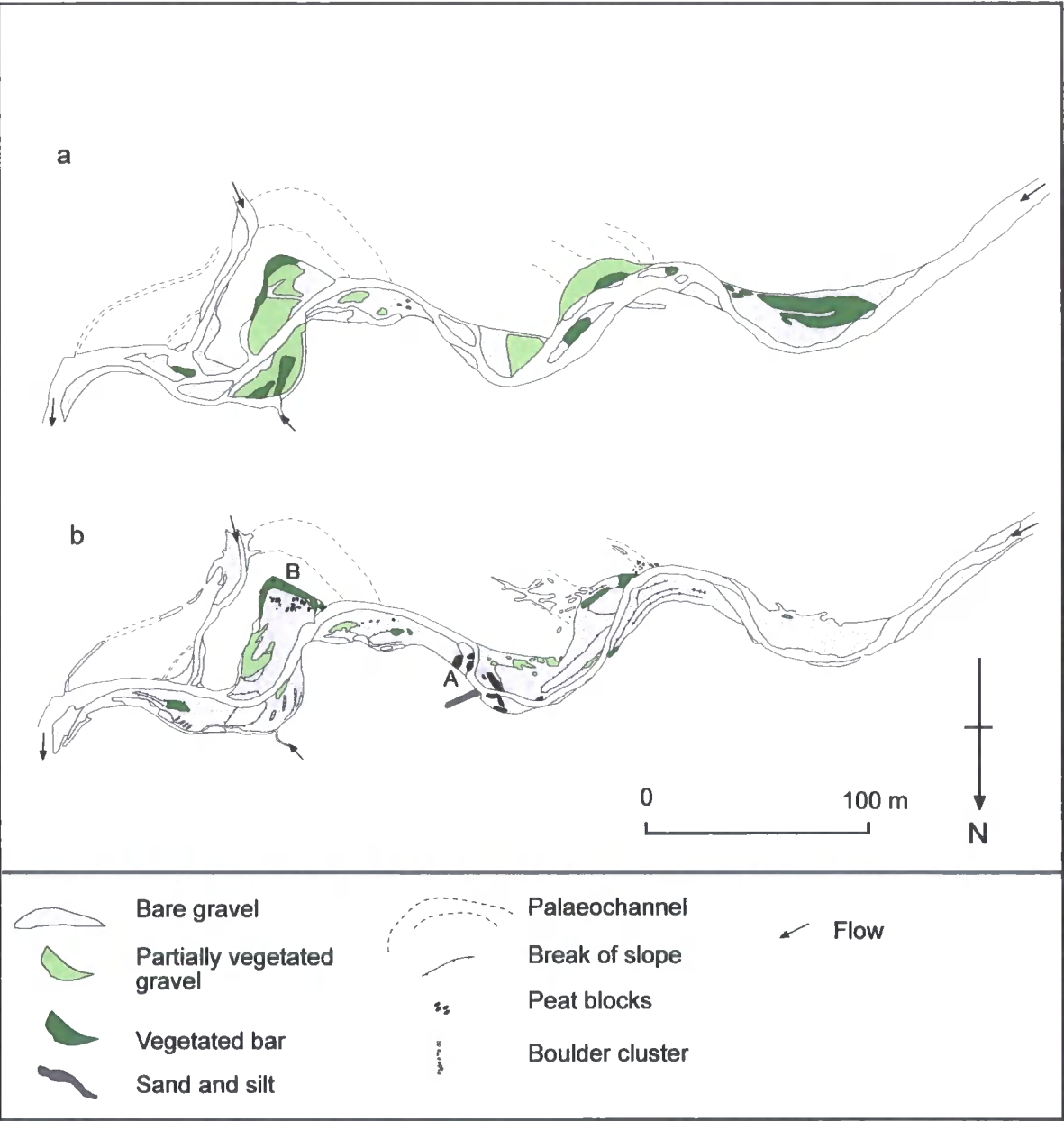


Figure 7.24 Large peat blocks deposited (a) close to source within the main channel of Trout Beck, note their local influence on bar sedimentation and (b) downstream on the 1969-1975 palaeochannel.

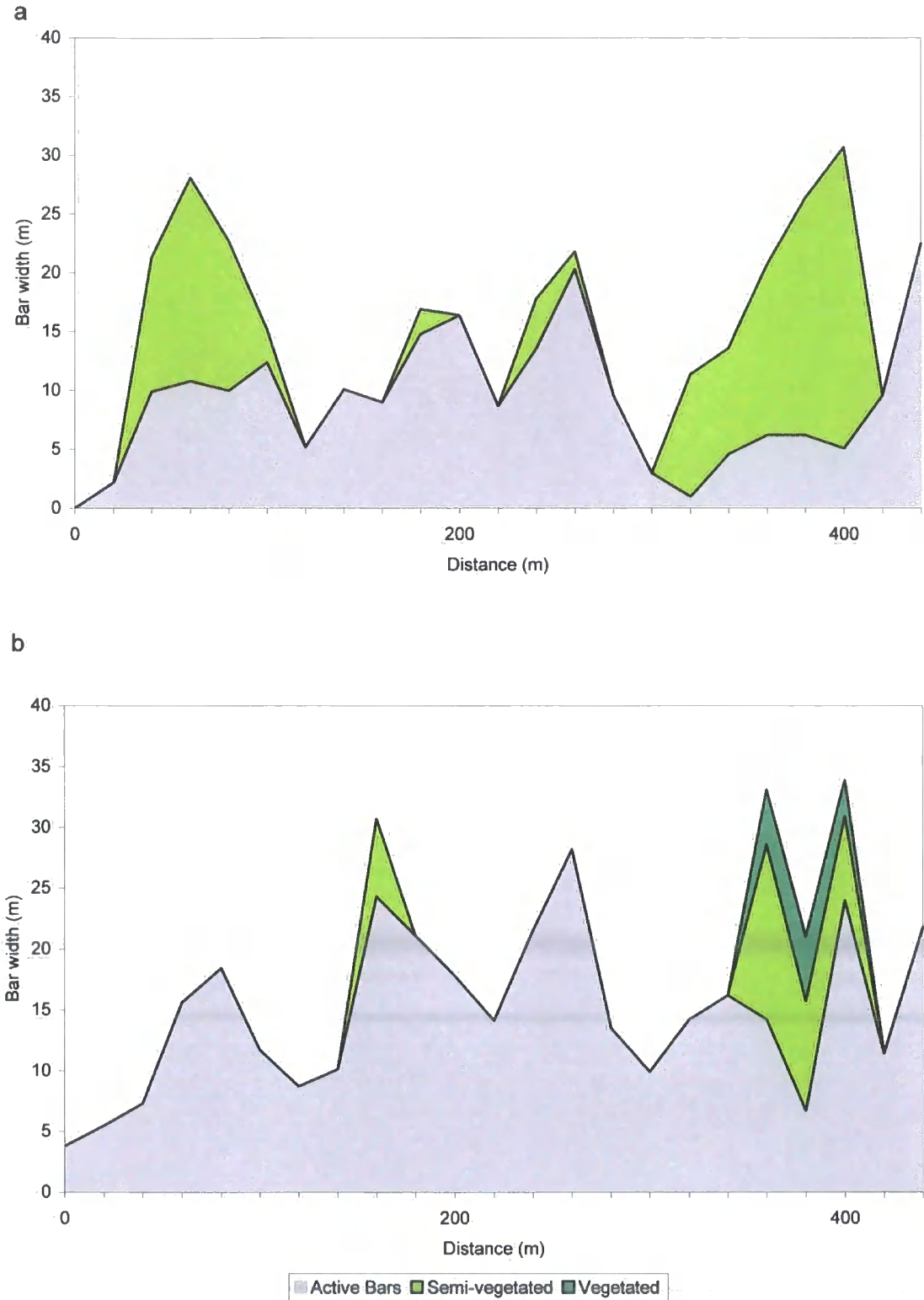
a



b



Figure 7.25 Bar widths along the Trout Beck Netherhearth Foot reach
(a) prior to the flood in June-July 2002 and
(b) subsequent to the flood during August 2002



7.4.4. Style of planform change associated with flood events.

The impact of the July 2002 flood on the river channel in the Trout Beck Ford and Trout Beck Netherhearth Foot reaches has enabled the identification of a series of channel change styles characteristic of a high magnitude event. The most significant change is a substantial increase in active gravel bar area due primarily to deposition but also reworking of the gravel bar surfaces (Figure 7.20). This change is particularly marked when the channel width series are compared (Figures 7.22 and 7.25). The distribution of sedimentation is strongly controlled by the elevation of the channel bed and surrounding surfaces such as former bars and the floodplain. Deposition is concentrated on existing active bar surfaces, which are also re-worked, and semi-vegetated bars (those active in the decades prior to the flood event) which tend to be at a low elevation. Sedimentation within surrounding palaeochannels, particularly where these meet the contemporary river channels, was recorded in both study reaches (Figure 7.19 and 7.23).

Diversions of the wetted channel occurred due to sedimentation within the pre-existing channel. This was observed most clearly in the Trout Beck Ford reach in the upper (Figure 7.20) middle (Figure 7.19 location A) and lower reach (Figure 7.21). In the case of the lower portion of the reach this led to diversion of flow across the floodplain (this was still evident during the summer of 2003). This change resulted in the majority of flow bypassing the pre-existing bend; further widening of the new channel will result in the complete abandonment of the bend. The removal of mid-channel bars was evident in both reaches. This appears to occur via a combination of two mechanisms. Deposition may preferentially infill one channel resulting in the concentration of flow into the other channel (examples can be seen on Figure 7.19 and 7.23). Alternatively, flow may excavate a new channel through the centre of the medial bars while deposition occurs within the former active channels. This type of change occurred in location A in the Trout Beck Ford reach (Figure 7.19).

The channel planform described above occurred within sedimentation zones. Field reconnaissance of flood impacts indicated that relatively low lateral confinement is essential for the types of change described above. Where lateral confinement is high channel erosion tends to dominate, principally involving bed scour and some bank scour. Where the channel is formed entirely within bedrock any sediment stored within such reaches is flushed downstream, becoming deposited where confinement declines. An excellent example of this effect occurred within the bedrock gorge which

separates the two Trout Beck study reaches (Figure 7.26). Here coarse sediment stored in the base of the channel was flushed downstream and deposited in the Netherhearth Foot reach. The marked increase in gravel bar extent in the upper portion of the Trout Beck ford reach was also caused by the flushing of sediment from the bedrock confined reach upstream (Figure 7.20). Bedrock control is important throughout the catchment and, as in Weardale, determines the degree to which channels respond to floods.

Figure 7.26 The bedrock gorge located between the Trout Beck Ford and Netherhearth Foot reaches. Note the relative absence of sediment in the bed of the channel, which was flushed out by the flood. The photograph was taken in early August 2002.



7.5 The cause of channel planform change in upper Teesdale

Many aspects of the channel planform changes recorded along the four study reaches over the historic period are very similar to the changes in channel planform produced by the flood of 30th July 2002. Chute channel formation leading to eventual bend cut-off was evident in the Trout Beck Ford reach in 1969 and the Netherhearth Foot reach during 1951. Bend bypassing such as this is encouraged by localised sedimentation within the channel and erosion of the bank during a flood event. The pronounced increase in the extent of gravel bars that occurred in the Crookburn Foot and High Crag Foot (Figures 7.13 and 7.15) reaches have similarities with the increases in gravel bar extent recorded along Trout Beck following the 2002 flood (Figure 7.23). In the middle reaches of the Crookburn Foot reach the pattern of mid-channel bar dissection and sedimentation in the former channels is very similar to that recorded in location A along the Trout Beck Ford reach (Figure 7.19). Given the lack of clear evidence for the progressive downstream movement of coarse sediment the occurrence of a flood appears to offer the best explanation for these changes. The bend bypassing that occurred along the Netherhearth Foot between 1975 and 1995 reach also appears to suggest the occurrence of a flood event (Figure 7.12). The sedimentation in these bends is similar to that seen in the upper bend of the Trout Beck Ford reach (Figure 7.20).

Correlating historic channel changes with specific flood events was not possible as reliable long-term (50 years) discharge records were not available for the catchment. Also the changes represent intervals of time of up to 20 years and a series of small floods over this period rather than a single large flood may have resulted in similar changes. However the flood changes observed in the Trout Beck reaches indicate that substantial changes can be initiated by a single event. The relatively small scale of the channel changes between 1969 and 1975 and 1995 and 2002 suggests that significant channel changes correspond to large floods. Gradual change over these periods and the progressive vegetation colonisation of bar surfaces represent a phase of channel adjustment following floods. For example, following chute channel formation in both the Trout Beck reaches it took a number of years before the entire flow was routed along the chute channel (Figures 7.11 and 7.12). The channel changes that occurred in the central portion of the Crookburn Foot reach from 1953 onwards suggest the re-occupation of secondary channels that were abandoned between 1911 and 1953 and are an example of such readjustment following a flood.

The mechanisms of channel planform change identified in upper Teesdale are summarised in Figure 7.27. All of these are changes that can occur rapidly during floods, with a, c, f and h being forms of change associated with the 30 July 2002 event.

However, flooding is not the only mechanism through which channel changes are initiated. The Trout Beck Ford reach shows evidence of possible anthropogenic modification of the river channel. The removal of the bend in the centre of the reach between 1953 and 1969 was coincident with the construction of a wall in this location (Figure 7.11). It is difficult to ascertain if the channel was deliberately altered with the wall constructed as a part of this scheme, or whether a flood led to the removal of this bend and the wall constructed merely to help re-establish channel stability. Similar walls, designed to help close-off abandoned channels, have been reported in the South Tyne catchment (Passmore et al., 1993).

Metal mining was also considered to be an important cause of planform change in Weardale, as is the case elsewhere in the North Pennines. A number of metal mines were located in the upper Tees catchment and hushing is known to have been practised in the upper reaches of Trout Beck and the River Tees (Figure 3.10). The impact of metal mining, which had ceased in the catchment by the end of the nineteenth century, is difficult to determine. However, inputs of coarse sediment may have accounted for the relatively high gravel bar areas in the sedimentation zones. For example, metal mining was practiced immediately upstream of the Crookburn Foot reach and this may account for the presence of extensive gravel bars, and perhaps even the formation of the mid-channel bars. Similarly, declines in bar extent during the twentieth century may reflect the cessation of metal mining in the catchment.

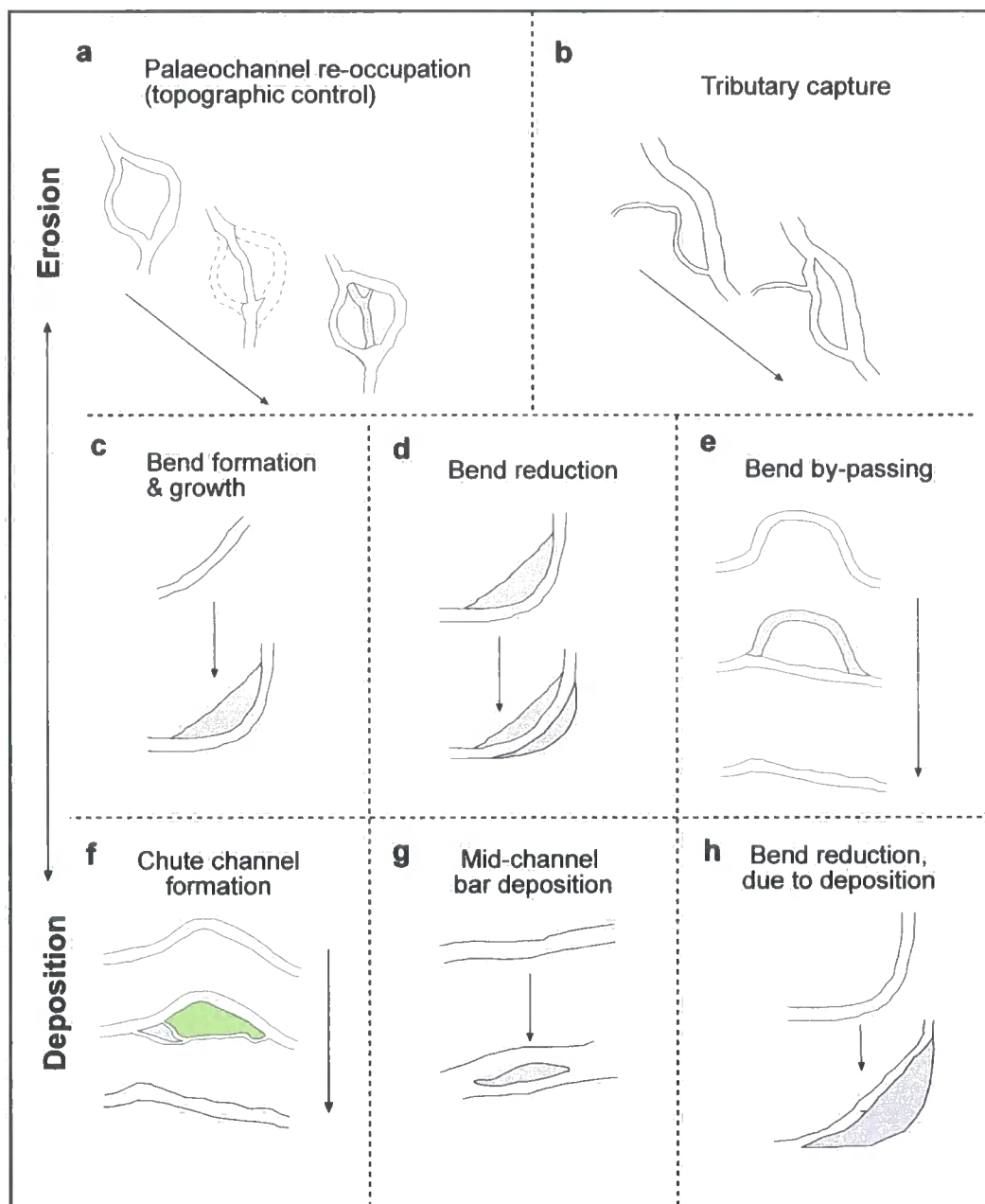
An interesting aspect of channel planform behaviour in the upper Tees catchment is the contrast in the degree of channel planform change prior to 1911 and following 1911. Prior to 1911 the channel planform within each of the sedimentation zones was relatively stable. However by 1953 significant changes in channel planform had occurred and the river channel continued to be subject to change in the following decades. As described above, the planform evidence points to the occurrence of at least one large flood in the catchment some time prior to 1953, and the nature of this evidence indicates this had recently occurred. The subsequent changes in channel

Figure 7.27 Styles of channel planform change associated with channel erosion and deposition recorded in upper Teesdale. Change typologies can be classified according to the dominance of erosion and deposition. Each of these change types occur rapidly during high magnitude floods.

a-b Erosion exploiting existing topographic lows.

c-e Bend changes through a combination of deposition and erosion.

f-h Change initiated by deposition within the channel.



planform represent post-flood channel adjustment (bar re-working), however the relative planform stability prior to the flood is difficult to explain. As discussed in the preceding chapters, the late nineteenth century was a time of relatively high flood frequency and magnitude, yet planform stability dominates in upper Teesdale at this time.

7.5. Conclusion

Initial investigations suggested that the channel planform of the River Tees in upper Teesdale was very similar to the channel planform of the Wear during the nineteenth century. However, statistical analysis of channel width series data indicated that this view is a simplification. Detailed reconstructions of channel planform changes during the historic period were made for four reaches. This revealed that the most significant changes in channel planform during this period occurred in the steeper Trout Beck reaches. The impacts of the 30 July 2002 flood event add further support to the view that flood frequency provides the primary control on channel planform change. In general two specific conclusions can be drawn:

1. The channel width series data from the upper Tees catchment indicates that the present channel planform of the upper Tees is of a form transitional between the planform of the River Wear during the years 1951 and 1991. Like the River Wear in 1951 the channel structure is composed of discrete sedimentation zones separated by relatively narrow intervening reaches. Yet these zones are less distinctive than those along the Wear during 1951, and overall gravel bar extents are more similar to those of the Wear in 1991. In upper Teesdale sedimentation zones are less spatially persistent and, particularly in the lower catchment, are characterised by large vegetated islands. There is considerable variation in channel width in these sedimentation zones, resulting in a time series structure transitional between the Wear in 1951 and 1991 where frequent but low magnitude variations in channel width structure dominate the channel width series results.
2. Evidence for the upper Teesdale catchment indicates that flooding is the dominant control on channel planform behaviour and this maintains the relatively large gravel bar extents. However, the decline in gravel bar area in

these reaches indicates that sediment supply to these reaches has declined over the last 150 years. The frequent occurrence of large floods and high channel gradient appears to be sufficient to maintain sedimentation along Trout Beck, however, their restricted extent (variable channel width) may be a result of the decline in sediment supply to these reaches which has occurred over the last 150 years.

These results reveal that the catchment has experienced a similar history of channel planform change during the historic period to that of Weardale. However, local influences such as catchment geomorphology, climate and the relative lack of large-scale anthropogenic channel modifications have resulted in significant differences in the contemporary planform structure. Clearly when considering the wider implications of historic channel planform change for an individual catchment (Weardale), care must be taken to reflect on the fact that the response of catchments to regional climatic changes and similar land use impacts (metal mining) is strongly modulated by local controls such as geomorphology and anthropogenic activities. Despite this, the impact of the July 2002 flood provides an important insight into the effects of large flood events on channel planform in upland rivers. This is particularly important given the relative lack of detailed information concerning the impact of the large nineteenth century floods on the river channels of the North Pennines.

Chapter 8 Discussion

8.1. Scope of chapter

Determining the relative importance of the different processes that influence channel planform represents a significant challenge. In this study climate and land use (mainly metal mining) were found to be significant at the upland catchment-scale and have influenced river channel behaviour throughout the last 150 years. Superimposed on these influences are local, reach-scale controls such as variations in metal mining technique (eg. hushing), local high magnitude floods and anthropogenic channel modification (gravel extraction or channelization). The relatively restricted scale of these operations is reflected in the duration of their impact, typically decades. In order to determine the cause of channel planform change and hence possible future changes in channel planform stability, the interaction of these processes must be evaluated and an assessment of process dominance be made.

This chapter is divided into three sections. The first provides a summary of the nature of river channel behaviour over the historical period in Weardale and upper Teesdale. Contrasts and similarities in channel behaviour between the two catchments are determined. The chapter then evaluates the range of processes identified in the results chapters as potential causes of channel change. First catchment-scale influences are considered, principally flooding and metal mining, followed by reach-scale factors, primarily channel modifications and local land use practices. The findings are compared to the historic channel behaviour of other British upland gravel-bed rivers. Finally the chapter attempts to determine the relative importance of processes driving channel change in the British uplands. The chapter concludes with a conceptual sediment budget for a typical North Pennine catchment.

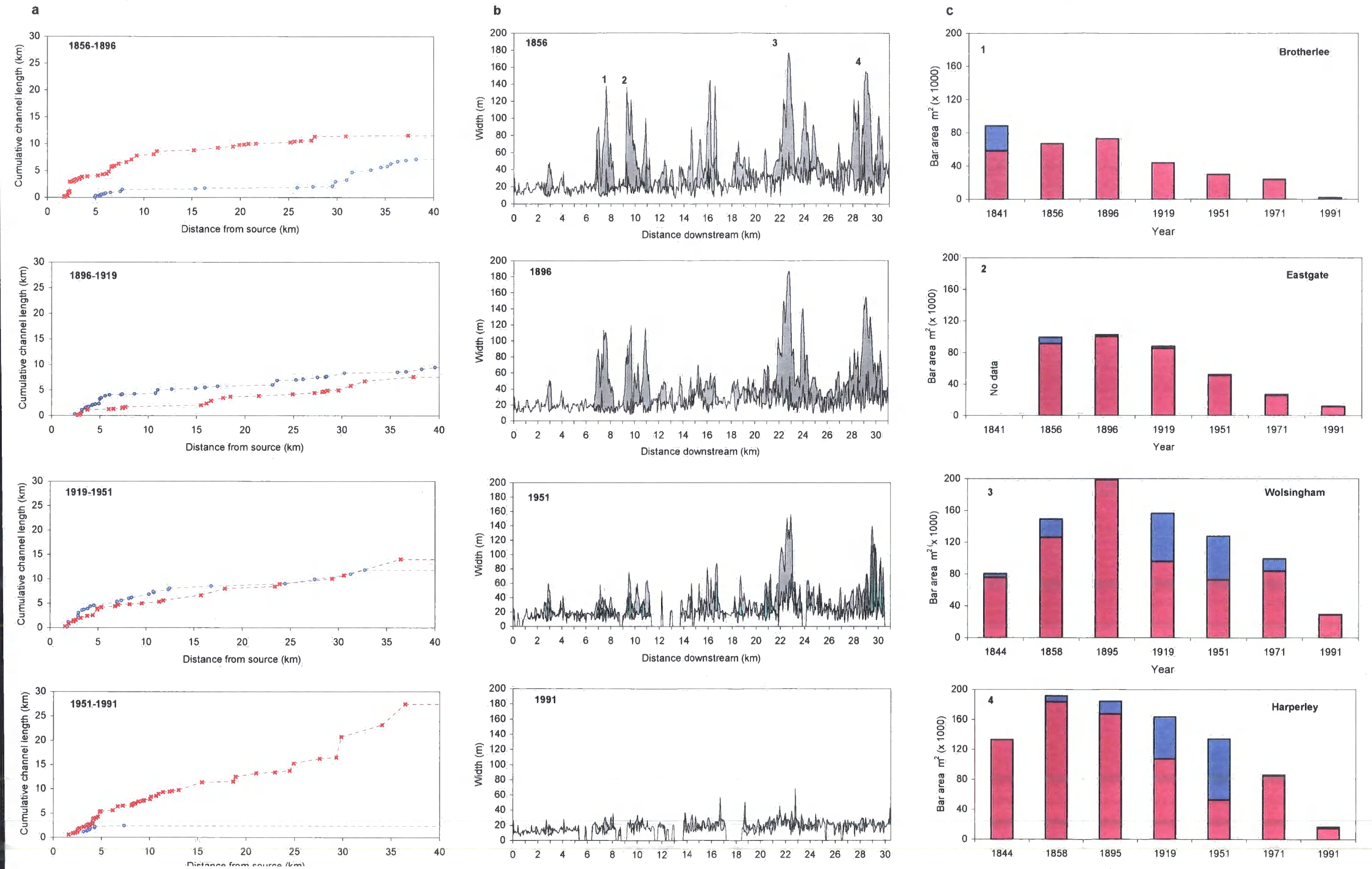
8.2. Historic channel planform change in Weardale and Upper Teesdale

8.2.1 Weardale

The catchment scale investigations (Chapter 4) indicated that three distinct episodes of river channel change could be identified in Weardale. First during the late nineteenth century, a decline in the extent of gravel bars occurred in the tributary channels and the upper reaches of the trunk channel, while in the lower reaches an increase in the extent of gravel bars occurred (Figure 8.1a). This contrast in sedimentation between the upper catchment (negative) and lower catchment (positive) suggests a transfer of sediment from the upper reaches of the catchment to the lower. During the early twentieth century the tributaries showed a tendency for increasing gravel extent, however, in the trunk channel a period of sediment reworking occurred. After 1919 all the study reaches were characterised by local sediment reworking with small increases and decreases in gravel bar area. Finally, during the second half of the twentieth century, a catchment-wide decline in the extent of active gravel occurred, indicating that all the study channels (except Ireshope Burn) experienced a decline in sediment supply (Figure 8.1a). These results demonstrate the value of catchment-scale investigations for determining changes in patterns of fluvial sedimentation. This also provided an initial indication of the likely controls on river channel behaviour (Chapter 4). The catchment changes were reflected in the behaviour of the trunk channel, allowing the impacts of catchment-scale events on the river channels to be quantified by measuring channel changes along the trunk channel.

The trunk channel width series (Chapter 5) indicated that the main changes in the extent of gravel bars between 1856 and 1896 were clustered into the discrete reaches with wide expanses of active gravel; these are classified as sedimentation zones within the catchment scale analysis. Changes during this period involved a decline in the extent of gravel bars in the upper sedimentation zones, and increases in gravel extent in the lower sedimentation zones (Figure 8.1b). The analysis confirmed the occurrence of localised gravel re-working between 1896 and 1951, but also revealed that the majority of the sedimentation zones showed a decline in the extent of active gravel bars. Finally between 1951 and 1991 the entire trunk channel showed a decline in the extent of gravel bars with both the sedimentation zones being completely abandoned and bars within intervening reaches showing a decline in their extent.

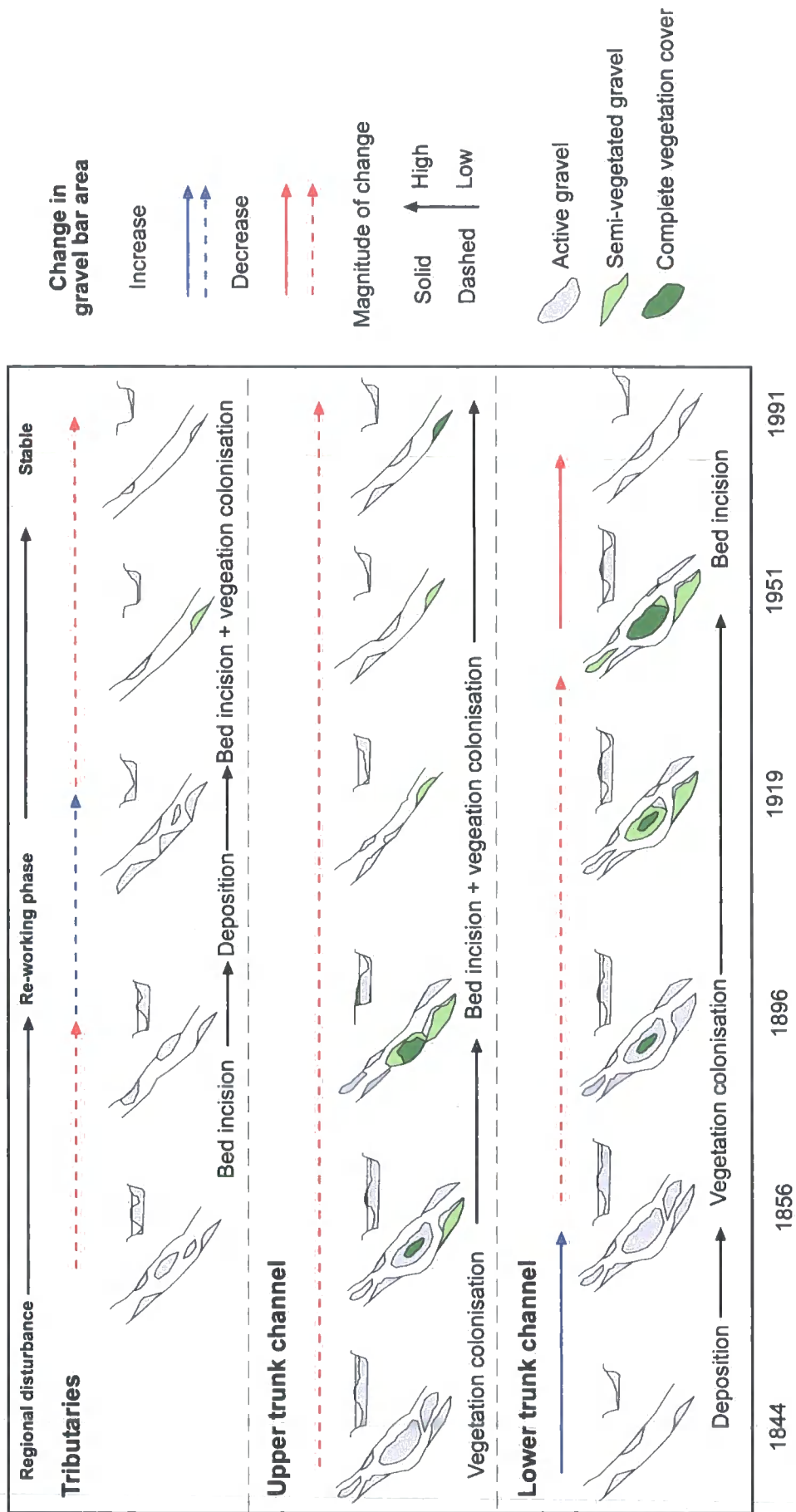
Figure 8.1 Summary of (a) catchment scale results 1856-1991, (b) trunk channel width series results (1856-1991) and (c) changes in bar extents for the four main sedimentation zones (see part b, 1856).



Reach scale investigations (Chapter 6) were conducted both to enable the detail of the channel changes within sedimentation zones to be determined (Figure 8.1c shows selected examples), and the impact of reach-specific controls on channel behaviour to be assessed. The reach scale investigations indicated that gravel bar extent peaked at some point prior to 1841 in the upper trunk channel (Brotherlee) but did not peak until as late as 1896 in the lower catchment (Wolsingham), with the most significant increase in bar extent occurring between 1844 and 1856 (Figure 8.1c). This confirmed that sediment transfer from the upper to lower catchment occurred, but that the main phase was prior to 1856. The sedimentation zones of the tributary channels, however, stored sediment until 1856, after which they showed a decline in the extent of gravel bars. The phase of localised re-working between 1896 and 1951, illustrated by the width series analysis, showed a general decline in the extent of active bars, with some localised re-working. Between 1951 and 1991 the decline in bar extent continued, with evidence from 1971 indicating that the decline occurred progressively over the period of 40 years.

The behaviour of the catchment over the historical period (approximately the last 150 years) can be summarised into a conceptual model (Figure 8.2). This shows three distinct episodes of channel behaviour over the historic period. During the early nineteenth century (prior to 1856) sediment supply to the tributary and upper trunk channel was high, characterised by extensive gravel bars and local channel braiding where lateral confinement was low. As the majority of the tributaries are laterally confined, relatively efficient sediment transfer from the tributaries in the upper catchment to the trunk channel resulted in a near synchronous pattern of channel behaviour. Where sedimentation zones had developed, the migration of sediment was interrupted by storage in bars. By 1856 however the lower catchment had also experienced an increase in the extent of gravel bars. Following this pulse of sedimentation the upper sedimentation zones began to stabilise through vegetation colonisation of their extensive bars after 1856, while stabilisation of the lower sedimentation zones did not begin until around 1896. Local reworking maintained bar extents in intervening reaches until the period 1951-1991 when these showed a decline in gravel bar extent.

Figure 8.2 Schematic diagram of channel planform change between 1844 and 1991 based on observations from sedimentation zones in Weardale. The principle cause of change is also indicated.



8.2.2 Teesdale

Analysis of historical maps (Chapter 7) revealed that during the late nineteenth and early twentieth centuries the planform of the river channels were relatively stable and characterised by extensive gravel bars, particularly in the upper reaches of the catchment. The extensive nature of the gravel bars in Teesdale at this time corresponds well to those of Weardale. The relative planform stability at this time, however, contrasted with Weardale, which showed changes in channel planform, primarily through re-organisation of gravel bars. Between 1911 and 1951 however, a marked increase in channel activity occurred, although the actual extent of gravel bars began to decline through vegetation colonisation. Subsequently the river channels continued to show a decline in the extent of gravel bars superimposed by local re-working, which persists to the present. Statistical analysis of the contemporary channel width series indicates that the present channel structure is similar in nature to that of the River Wear during 1951 (alternating wide and narrow sections) but also shares some characteristics with the channel of 1991 (relatively low width variability).

The contrast in degree of channel activity between upper Teesdale and Weardale during the nineteenth century (and also between the nineteenth and twentieth centuries in upper Teesdale) is difficult to reconcile. The results from Weardale and other studies indicate that the presence of extensive gravel bars corresponds to high rates of channel planform activity (high sediment supply). Channel planform in upper Teesdale appears to have been stable during the nineteenth century, perhaps because it was adjusted to sediment supply and the flashy regime of the catchment, as is common in Scottish gravel-bed rivers (Werritty and Leys, 2001). Channel instability in both Trout Beck study reaches appears to have been initiated by flood-induced channel straightening. Both had stable sinuous planforms until the mid-twentieth century. It is likely that gradual sedimentation in these reaches during the nineteenth and early twentieth centuries made the channels increasingly sensitive to floods as the declining channel capacity caused the channel to build towards a change threshold. Indeed the transformation of both these reaches initially involved localised avulsion, known to be promoted by localised aggradation (Warburton et al., 2002). During the twentieth century the Trout Beck study reaches declined in sinuosity resulting in higher channel gradients which promoted localised incision and sediment reworking, enhancing planform instability. The reduction in channel sinuosity also concentrated gravel bars into a narrower channel belt. In contrast the

lower gradient Tees reaches have only shown minor planform changes associated with the movement of coarse sediment downstream.

8.3. The cause of channel planform change in the North Pennines

8.3.1 Catchment-scale influences

Channel planform at the catchment-scale is determined by the interaction of climate, geology and land use. Changes in channel planform however are driven by changes in either climate and land use, the extent of which is governed by geological and topographic influences primarily through channel confinement. Changes in regional climate circulation influence the behaviour of an entire catchment through changes to the average temperatures (sediment supply can be influenced by the incidence and severity of winter frosts) or changes to flood frequency and magnitude. The impact of changing flood frequency is complicated by the occurrence of localised intense storms which led to spatial variation in process rates. Similarly, in order for land use to influence channel behaviour throughout an entire catchment it must be so extensive that it impacts on the majority of the catchment. In Weardale metal mining is known to have been practiced throughout much of the catchment, indeed the Waskerley Beck catchment is the only tributary catchment of Weardale that was not mined (Figure 4.16). Waskerley Beck provides a useful control when determining the impacts of metal mining.

8.3.1.1 Annual temperatures

During the nineteenth century the climate was ameliorating following the harsh conditions of the Little Ice Age (LIA) and this is likely to have had an impact on geomorphological processes in the catchment (Higgitt et al., 2001). During the seventeenth and eighteenth century colder winters are thought to have increased freeze-thaw rates which led to enhanced slope activity and as a result increased the quantity and rate of sediment delivery to river channels (Passmore et al., 1993). Enhanced freeze-thaw activity during this period reflects the harsh climate of the LIA which persisted throughout northern, western and central Europe at this time (Rumsby and Macklin, 1996). The severe nature of the climate at this time is indicated by the frequent occurrence of severe winter snowstorms during this period. In particular, between 1740 and 1800 fourteen severe snowstorms were recorded in

Weardale (1740, 1748, 1749, 1762, 1764, 1765, 1767, 1783, 1785, 1789, 1795, 1796, 1799, 1800) (Egglesstone, 1871). Slope processes will have been enhanced by a reduction in vegetation cover associated with this harsh climate; indeed, landslides were more common during the LIA (Grove, 1988). In addition to slope activity, river bank erosion is enhanced by freeze-thaw processes. For example Blacknell (1981) found that bank erosion is greatest when freeze-thaw activity occurs.

Climate deterioration during the LIA resulted in increased storminess producing a landscape that was more sensitive to change (Higgitt et al., 2001). Increased storminess was concentrated into phases of climatic transition. Enhanced fluvial activity occurred in river catchments in Europe during the period 1750 to 1900, corresponding with the warming phase at the end of the LIA; indeed a phase of river activity also occurred during the climatic cooling at the beginning of the LIA (1250-1550) (Rumsby and Macklin, 1996). The main phase of relatively constant cool climate between 1550 and 1750 was however associated with low rainfall totals, resulting in a low frequency of competent flows and as a result limited slope-channel coupling (Rumsby, 2001). It is likely that slopes and channels became more effectively coupled at the end of the LIA as flood flows increased. The onset of peat erosion in upland catchments during the LIA (Stevenson et al., 1990) may also have increased the availability of coarse sediment as many peat gullies eroded into the substrate, consisting of till and periglacial deposits. The increased availability of coarse sediment in the catchment may partly explain the extensive gravel bar areas which characterised the river channels of Weardale and upper Teesdale during the mid-nineteenth century. Such gravel bars are particularly common in the upper catchment, where the climate is harsher and gullied blanket peat areas are widespread.

8.3.1.2. Floods

The relationship between climate circulation and flood frequency and magnitude is now widely accepted as a primary control on channel planform change (Higgs, 1987; Newson, 2003). The impact of changes in flood frequency and magnitude on the river channels of in Northern England has been examined by various workers including Passmore et al. (1993), Rumsby and Macklin (1994 and 1996), Merrett and Macklin (1999) and Coulthard and Macklin (2001). These studies have focused on investigating the influence of clusters of flood events of different magnitude (related to changes in climate) derived either from documentary sources or inferred from

geomorphological and sedimentological evidence (Macklin et al., 1992 a and b, Macklin et al., 1994). The impact of flood frequency and magnitude has been a central research theme and lies at the core of our understanding of river channel behaviour in upland catchments. Indeed, Macklin (1999) argues that the competence-limited nature of coarse gravel-bed rivers means that their behaviour is closely related to climatically driven variations in flood frequency and magnitude.

The pattern of sedimentation in Weardale was compared to the flood history of the catchment in chapter 4 (Figure 4.8). In Weardale the mid-nineteenth century was characterised by relatively extensive gravel bars in the tributary channels and upper trunk channel, which subsequently declined in extent between 1856 and 1896. These extensive bars originated during a phase of deposition prior to the 1840s, as indicated by the tithe plan evidence from Brotherlee (Chapter 6), and also from Swinhope Burn (Warburton et al., 2002). This deposition was coincident with a phase of zonal climate circulation which in the Tyne catchment was characterised by channel aggradation, particularly in trunk streams (Rumsby and Macklin, 1994). The large floods of the 1820s (Figure 4.8) appear therefore to have delivered sediment to the tributaries and trunk channel. The decline in gravel bar extent between 1856 and 1896 coincided with the change to a meridional climate between 1875 and 1894 (Figure 4.8). This period was characterised by a clustering of large floods during the late 1870s and early 1880s in Weardale and this may have been responsible for the transfer of sediment downstream from the upper dale. Significantly, however, the cartographic evidence (Chapter 6) indicates that the increase in gravel bar area in the lower dale began prior to 1856. While the large floods of the 1870s and 1880s contributed to the transfer of sediment from the upper to lower catchment, the declines in gravel bar area in the upper catchment and the transfer of sediment to the lower catchment were initiated by the large floods of 1822, 1824, 1828 and 1837 (Figure 4.8). The floods of the nineteenth century were clearly of significance in the context of the distribution of sediment within the catchment between 1841 and 1896.

The impact of the flood event of 30 July 2002 in upper Teesdale confirms that large floods can cause substantial increases in active gravel extent through local deposition. This provides a useful analogy for floods in Weardale, as this flood was not accompanied by widespread slope activity. Channel-only floods (c.f. Newson 1980a) predominate in the lower reaches of upland catchments where slopes and channels are decoupled by terraces and floodplains. The pattern of erosion and deposition during a flood is strongly influenced by the degree of lateral confinement,

with deposition being concentrated in unconfined reaches (Macklin, 1997d). Several planform features were found to be typical of flooding, including: channel division involving chute channels and in-channel sedimentation; overbank sediment deposition; bend cut-offs and out of channel flow. In addition to deposition within the channel and over bank, gravel bar re-working during floods also increases the area of active gravel. Relating the impacts of this flood to earlier changes in channel planform in upper Teesdale indicates that many of the significant changes in channel planform appear to relate to the impact of large flood events (Chapter 7).

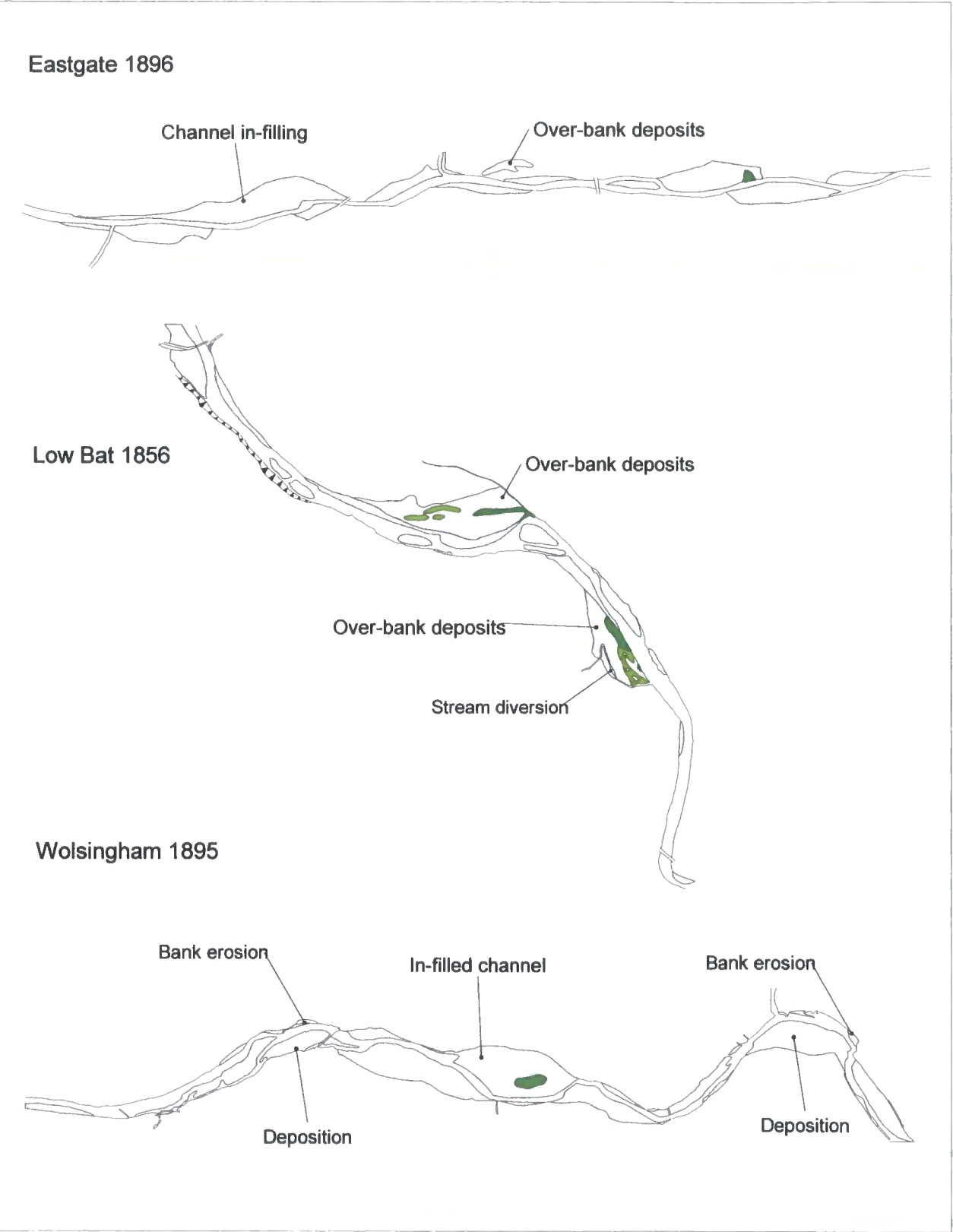
Evidence pointing to the importance of flood events as a primary control on channel planform, in Weardale, is provided by the detailed reconstructions of channel planform changes (Chapter 6) in relation to the occurrence of large floods. Table 8.1 provides a series of documentary accounts describing the impact of nineteenth century flooding in Weardale. The importance of these floods is clear when these accounts are compared to examples of channel planform change from the late nineteenth century (Figure 8.3). At Eastgate the bend cut-off, in-filling in the upper reach and over bank deposition in the middle reach between 1856 and 1896 (Figure 8.3a) are characteristic of the styles of changes observed in upper Teesdale (Figures 7.20 and 7.24). The channel planform reconstruction of 1856 at Low Bat (Figure 8.3b) shows evidence of extensive over bank spreads of gravel in at least two locations. These deposits correspond well with the description of the 1822 flood in the vicinity of Stanhope (Table 8.1); the reach is located 1.5 km downstream from Stanhope. Of particular significance is the excellent correspondence between the description of the impact of the 1881 flood at Wolsingham and the changes recorded on the 1896 Ordnance Survey Plan (Figure 8.3c). The mid-channel bar located upstream of the main weir (high dam) corresponds well to the description provided by Egglestone (1881) (Table 8.1) and the bend changes downstream of the confluence of Waskerley Beck can also be discerned on the planform reconstructions (Figure 8.3 c). The impact of this flood accounts for the peak of gravel area occurring in 1896 in this reach rather than earlier.

Although the detailed accounts of flood impacts tend to be localised, clustering around Stanhope and Wolsingham (Table 8.1), this does not mean impacts were restricted to these locations. Stanhope and Wolsingham are the two largest population centres in Weardale, therefore significant impacts would be recorded preferentially in these areas. In more remote areas of the dale, or sections of the

Table 8.1 Accounts of large flood events in Weardale between 1800 and 1900.

Year	Description of event	Summary of the extent of impacts
1822	<p>" 'Nicholson's Flood,' on February 2nd, 1882, is handed down at Stanhope as one of those extraordinary floods which are seldom witnessed" (Egglestone, 1881, p4)</p> <p>"Significant problems for river side dwellers, especially in middle reaches. At Stanhope where haugh lands were covered, the occupants of Unthank corn mill had to leave for safety. Butts house was inundated and could not be approached without wading through water four feet deep. Field walls were thrown down and fields were covered with sand and stones" (Archer, 1992).</p>	River Wear around Stanhope
1824	<p>"A terrible thunderstorm during which a great number of people and cattle were killed in the North of England. The storm was most terrific at Swinhope in Weardale, a torrent of rain having fallen which swept away Swinhope stone bridge and brought down several large pieces of peat moss. A large portion of the wall which supported Harthope Road at St. John's chapel. Part of the road was taken away... At Westgate the Middlehope Burn carried away the turn pike road at the West end of the stone bridge at this village. On Westernhope side in Mr Stephenson's ground a large quantity of water, which had collected and distended a tract of swampy land, burst and swept down the Hope with such impetuosity that the stone bridge at Westernhope Burn was entirely swept away. This flood was considered the greatest since 1792" (Egglestone, 1881 p4-5).</p>	Swinhope Burn and possibly North and East Grain and Ireshope Burn in view of the reference to flooding at St. John's Chapel.
1831	<p>Snow storm on 4th February 1831 " and on the breaking up of the snow the rivers Tyne, Tees and Wear were flooded to an unusual height which resulted in considerable damage being done" (Egglestone, 1871 p5).</p>	Entire catchment
1846	<p>"...a most violent thunder storm, accompanied by torrents of rain. A great flood occurred in the several tributaries of the Wear, and considerable damage was done. Harthope Burn carried away a large portion of the wall which supported Harthope Road at St. John's chapel. Part of the road was taken away... At Westgate the Middlehope Burn carried away the turn pike road at the West end of the stone bridge at this village. On Westernhope side in Mr Stephenson's ground a large quantity of water, which had collected and distended a tract of swampy land, burst and swept down the Hope with such impetuosity that the stone bridge at Westernhope Burn was entirely swept away. This flood was considered the greatest since 1792" (Egglestone, 1881 p4-5).</p>	Right bank tributaries and middle reaches of River Wear.
1856	<p>Flood of 28 September "one of the highest floods... almost within living memory" (Fordyce, 1867,)</p>	The entire catchment.
1881	<p>Melting snow and rainfall combined to cause a severe flood event:</p> <p>"At Stanhope the southern half of the railway bridge collapsed when it was overtopped... Houses were flooded at The Butts, Unthank Mill, Newton and Shittlehope burn bridge on the way to Frosterley was washed away" (Archer, 1992 p 75).</p> <p>At Shittlehope Farm "the rush of the water took away the south pier of this bridge [the road bridge], and the south half of the iron structure fell into the river... The northern half and the north pier were completely washed away, and the approach road for several hundred yard, and a quantity of land on the west side were swept out by the great torrent". (Egglestone, 1881 p10).</p> <p>"[the flood] raised the bed of the river several feet between the two bridges in question [the road bridge and railway bridge 200 m upstream] and formed a new channel right through where stood the north pier and approach road of the Shittlehope burn structure". (Egglestone, 1881 p10).</p> <p>"In the Wolsingham district where the river bed is wide and immense gravel beds exist, considerable damage was done. Immediately above the high dam [weir] the river entered the north bank and carried away part of the main road" (Egglestone, 1881 p11).</p> <p>"Below Waskerley foot the stream rushed against the north side, carrying away a considerable quantity of the first and second fields, and about one hundred and thirty-three yards of the Wolsingham out-let sewer were destroyed, owing to the disappearance of this land.... The fields in some parts were covered with gravel, in others, in others sand had accumulated, and field walls lay broadcast where the flood has swept" (Egglestone, 1881 p11-12).</p> <p>"The bed of the river in some places was considerably altered. Below Stanhope Railway Bridge, and above high dam near Wolsingham, the river bed was several feet higher, and in some places the Wear had made itself new channels" (Egglestone, 1881 p11).</p>	The entire catchment.
1900	<p>6 October "Very wild and wet; the greatest flood on the Wear for many years" - Rainfall observer at Eastgate (all Saints Vicarage) (Law et al, 1998).</p>	Upper Weardale including tributaries.

Figure 8.3 Examples of river channel changes indicative of flooding in Weardale.
In each case flow is from left to right.



trunk channel distant from property or good farmland, details of flood impacts are likely to have gone unrecorded. However, the occurrence of intense local storms even in relatively remote locations is well documented (1824 and 1900).

Following this phase of sediment transfer within the catchment (1840s-1896) there followed a phase of re-working of gravel bars throughout the catchment between 1896 and 1951. Importantly this period was also characterised by a decline in the extent of gravel bars in the sedimentation zones along the trunk channel of the catchment. Sediment re-working was concentrated around gravel bars located close to the wetted channel. This re-working is likely to have been driven by the moderate annual floods, as large floods (recorded in the flood chronology) had declined substantially (Figure 4.8). This decline in large flood events accounts for the decline in the extent of the wide gravel bars of the sedimentation zones, which became increasingly vegetated. This phase of re-working was coincident with a phase of intermediate climate circulation, and in the Tyne catchment such periods were also characterised by local sediment transfers (Rumsby and Macklin, 1994).

Channel changes during the twentieth century were dominated by a decline in the extent of gravel bars, initially only affecting the sedimentation zones (with some local sediment reworking), before extending to the intervening reaches after 1951. This period was characterised by a continued decline in the frequency and magnitude of large flood events in the Wear catchment, as indicated by the long-term Wear flood record from Durham (Figure 4.8). The zonal (1920-1954) and meridional (1955-1969) climatic phases do not appear to have had the same impact on river flooding in the Wear catchment as they did during the nineteenth century. In the Tyne catchment however, widespread channel incision occurred between 1955 and 1969, coinciding with meridional climate circulation (Rumsby and Macklin, 1994). Yet in Weardale there is no clear field evidence for widespread channel incision being concentrated into this period. Maps and aerial photographs (chapter 6) indicate a gradual decline in the extent of active bars (through vegetation colonisation) occurred during the twentieth century. This reflects a continued decline in sediment delivery and the frequency of bar inundation following the decline in flood frequency and magnitude. The contrasting relationship between climate circulation and flooding between these catchments during the twentieth century requires further investigation (Table 8.2).

Table 8.2 Total number of floods recorded in the Tyne and Wear catchments, figures in brackets indicate the mean number of floods per year.

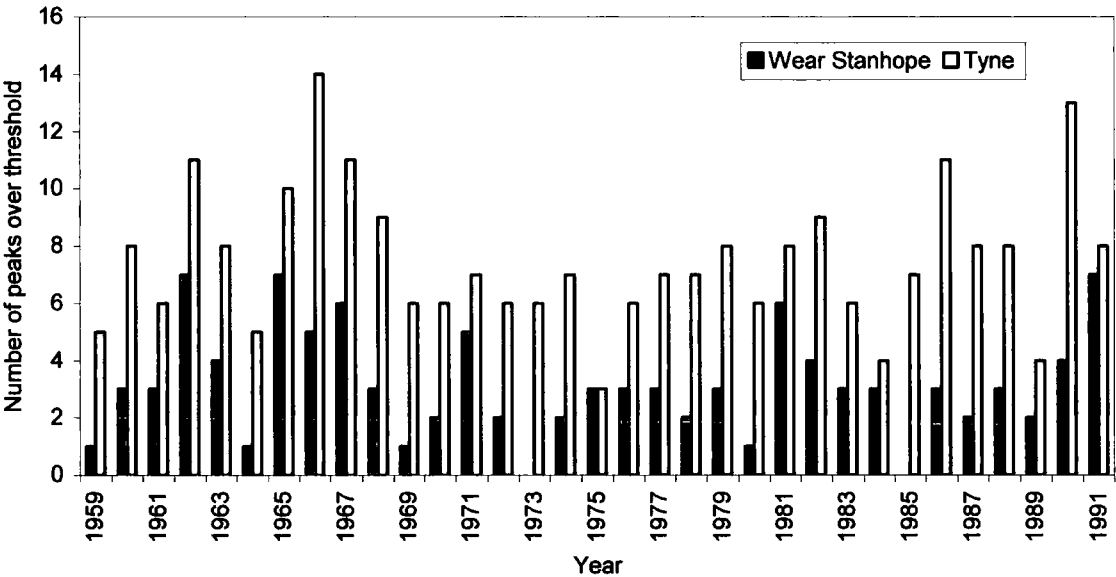
Time interval	Climate circulation	River Tyne (Rumsby and Macklin, 1994)			River Wear (Law et al, 1998)*
		Total number of floods	Total number of large floods	Total number of moderate floods	Total number of floods
1820-1874	Zonal	30 (0.55)	7 (0.13)	12 (0.22)	9 (0.17)
1875-1894	Meridional	12 (0.63)	3 (0.16)	4 (0.21)	6 (0.32)
1895-1919	Intermediate	10 (0.41)	1 (0.04)	3 (0.13)	2 (0.08)
1920-1954	Zonal	19 (0.56)	3 (0.09)	6 (0.18)	4 (0.18)
1955-1969	Meridional	18 (1.28)	3 (0.21)	3 (0.21)	1 (0.07)
1970-1979	Intermediate	5 (0.55)	0 (0)	1 (0.11)	1 (0.11)

*Based on Archer (1987).

The flood frequency data (Table 8.2) for the Tyne catchment were derived from a range of sources (Rumsby and Macklin, 1994), however the Wear flood record consists only of floods greater than $300 \text{ m}^3 \text{ s}^{-1}$ recorded at Durham (Law et al., 1998). The total number of floods recorded since 1820 in the Tyne catchment does seem to show the link between climate circulation and river flooding (Table 8.2). Yet this data does not match the Wear flood record. The Wear flood record appears best to reflect the record of large floods in the Tyne catchment. Differences in the flood records are likely to be as a result of differences in their derivation. The flood record for the Wear at Durham provides a record of the largest known floods on the Wear, while the Tyne flood data is apportioned into relative magnitude categories by a comparison of historic discharge estimates, derived from reconstructions of flow competencies from boulder deposits in an upland tributary of the Tyne, to gauged discharges (Rumsby and Macklin, 1994). The record of large floods in the Tyne catchment shows an increase in the frequency (mean number of floods per year) of large floods during meridional phases, as does the Wear during the nineteenth century. However the Wear record for the twentieth century does not show this pattern, with only one large flood occurring during this meridional phase.

Both the Tyne and Wear flood records reflect the entire catchment of each river and are not specific to the upland components of the catchment, although the Tyne record is partially derived from the upland catchment. As a result changes in flood frequency and magnitudes in the lower catchment may not reflect the behaviour of the upper catchment. The incidence of flooding in particular may vary considerably throughout a catchment as increasing tributaries join the main channel. Figure 8.4 compares the number of peaks over a threshold (floods) (threshold defined by Jeremy Brett Associates) for the upper catchment of the Wear (Stanhope) as compared to an aggregate record for the Tyne catchment.

Figure 8.4 Total number of peaks over a threshold for the River Wear at Stanhope*, and for the River Tyne† from 1958 to 1991. *Source: Environment Agency †Source: Rumsby and Macklin (1994) derived from four gauging stations in the lower North Tyne (2), lower South Tyne (1) and lower Tyne (1).

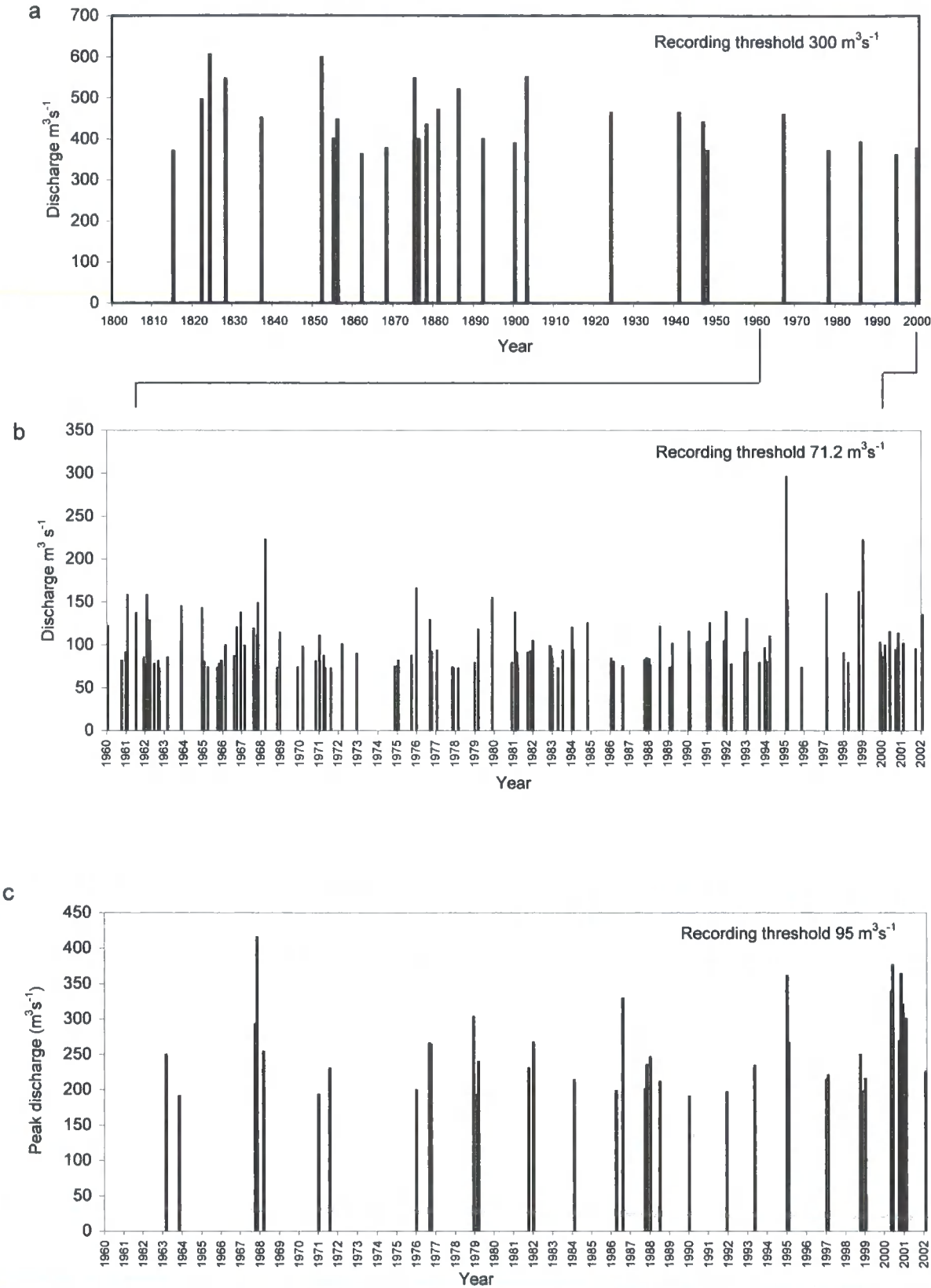


The aggregated Tyne record contains more floods for each year than does the Weardale record. This is due to the far greater catchment area of the Tyne as compared to Weardale, and the location of the North Tyne catchment up to 60 km north of the Weardale. This may account for the greater incidence of flooding as weather systems take longer to move across the Tyne catchment and smaller weather systems may affect the North Tyne catchment but not the South Tyne or Weardale. Significantly the general trends in the data set appear to correspond. The meridional climate phase appears to be detectable as an increase in flood frequency in both the Tyne and Weardale.

The reliability of catchment-wide reconstructions of flood magnitude and frequency can be evaluated for the Wear catchment by comparing the recent part of the long-term flood record with gauged discharge from the River Wear at Stanhope (Weardale) and Sunderland Bridge near Durham (threshold defined by Jeremy Brett Associates for Stanhope and the Environment Agency for Sunderland Bridge) (Figure 8.5). The occurrence of floods in Weardale between 1800 and 2000 was estimated using the historic flood discharge reconstructions made for the River Wear at Durham (Figures 4.8 and 8.5 a). Relating the flood record at Durham to events in Weardale is not straightforward. The large floods of 1967, 1978 and 1986 recorded in the Wear record (the occurrence of which is confirmed by Sunderland Bridge record (Figure 8.5c)) did not have particularly significant flood peaks at Stanhope (Figure 8.5b). Similarly, the Stanhope record (Figure 8.5b) indicates that flood frequency and magnitude was relatively high during the meridional phase between 1960 and 1969 but this was not detected in the Durham record. It appears that, despite being a phase of significant flooding in Weardale during the late twentieth century, the meridional period of the mid-twentieth century had no significant impact on flooding in the lower Wear (Durham). The lack of correspondence between Weardale and Durham may be explained by different hydrological functioning of the Wear catchment under different synoptic conditions. For example, tributaries downstream from Weardale can augment a flood, increasing its impact downstream (Durham). Conversely where floods originated from a local source within the Wear catchment (such as Weardale) downstream channel capacity and floodplain storage diminishes the magnitude of the flood.

Despite this lack of a good correspondence during the twentieth century, documentary sources (Table 8.1) indicate that many of the large floods of the nineteenth century did occur in Weardale. The larger floods (those of $500\text{m}^3\text{s}^{-1}$ or more at Durham) affected a greater proportion of the catchment upstream, the long-term flood record for Durham therefore providing a good indication of the occurrence of very large flood events in Weardale over the historic period. The Tyne flood history derived from a range of sources is affected in a similar manner. In order to determine the actual impacts of flood events in upland catchments, documentary accounts must be used in conjunction with generalised flood chronologies and where possible field evidence (datable flood deposits). This is particularly significant in upland catchments where localised convective storms can lead to variations in channel behaviour (such as in Ireshope Burn), which may not produce significant downstream floods (Carling, 1983 a,b). Documentary sources are particularly useful as the preservation of flood

Figure 8.5 Historical flood record for the River Wear at (a) Durham compared with peaks over a threshold at (b) Stanhope and (c) Sunderland Birdge. Sources: (a) Law et al., 1998, (b and c) Environment Agency.



deposits is uneven through a catchment, and is often limited in trunk channel settings. Where surrounding riparian land is used for agriculture, flood deposits are often removed.

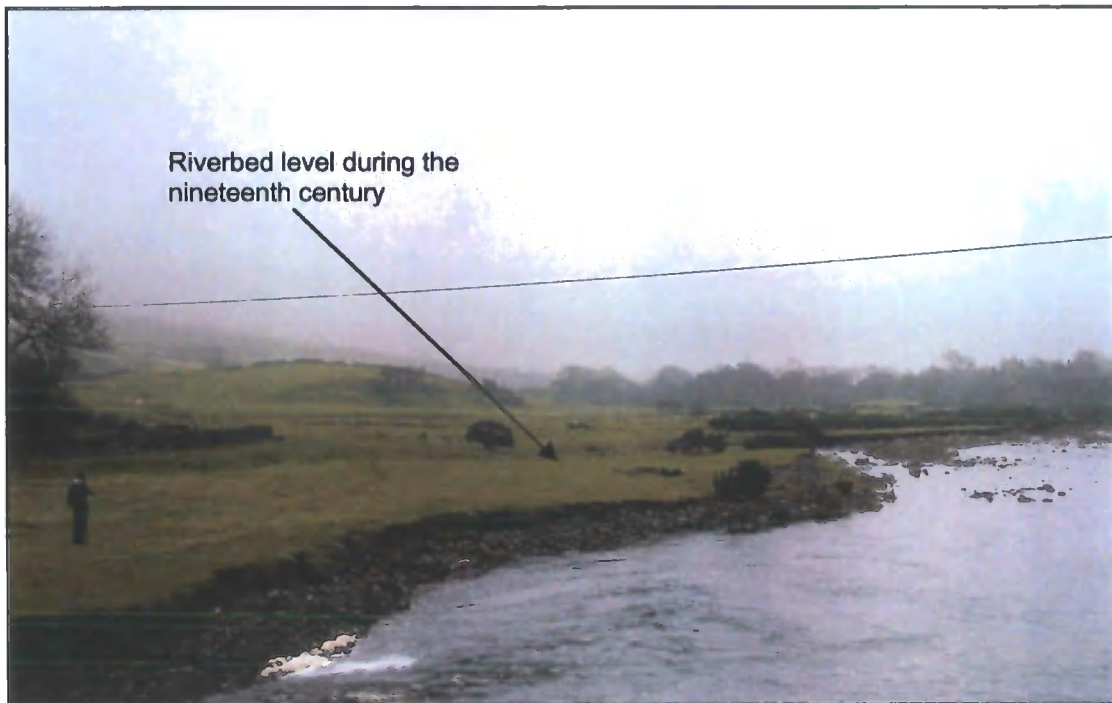
What is clear from the Wear flood record is that both flood frequency and magnitude declined during the twentieth century. The decline in flood magnitudes has implications when trying to establish the relationship between climate circulation and river flooding. Unfortunately the flood magnitude classification provided by Rumsby and Macklin (1994) does not provide change in actual magnitudes for the Tyne catchment. The Wear flood record indicates a decline in the strength of the linkage between river flooding and climate circulation during the twentieth century. This may reflect the shorter duration of both zonal and meridional climate circulation patterns during the twentieth century as compared to the nineteenth century (Table 8.2).

The behaviour of the river channel in Weardale appears to correspond well to the history of flooding within the Wear catchment as a whole. The nineteenth century was characterised by periods of frequent high magnitude floods which affected both the upper and lower catchments. Sediment released and transferred during these floods will have contributed to the extensive gravel bars of the late nineteenth century. The twentieth century was marked by low flood frequencies and magnitude. Even the meridional climate phase between 1955 and 1969 was not comparable in terms of flood frequencies and magnitude with the nineteenth century. As a result, gradual declines in bar extents occurred as the frequency and extent of bar inundation and reworking declined and the amount of sediment transferred through the catchment was reduced.

Recent research suggests that bed incision in the Tyne catchment between 1955 and 1969 may in fact have been a result of widespread mid-twentieth century gravel extraction operations (Archer, 2003; Archer pers com), adding further uncertainty as to the significance of the meridional climate phase during the twentieth century. In Weardale the only clear evidence of a phase of bed incision during the 1950s and 1960s occurred in the vicinity of gravel extraction operations (chapter 6). Generally, channel behaviour in Weardale responded to the decline in flood magnitude and frequency during the twentieth century, with local disruptions due to gravel extraction. There is some evidence of bed incision in the absence of gravel extraction operations in the former sedimentation zones of Weardale (Figure 8.6), however this appears to have occurred gradually during the twentieth century, due to a decline in sediment

supply. A combination of increasing confinement from vegetating lateral bars and moderate floods with limited sediment load appears to have encouraged bed incision.

Figure 8.6 Photograph illustrating bed incision (1-2 metres) since the late nineteenth century at Brotherlee. The former riverbed during 1844 is now vegetated, and forms the floodplain along the left bank.



8.3.1.3 Metal mining

As discussed in chapter 2, metal mining has been linked to increases in both coarse and fine sediment delivery to river channels. Coarse sediment can be delivered either through erosion of spoil or through onsite processing but, perhaps more importantly, by hushing. There remains considerable uncertainty as to the actual quantities and mechanism of delivery of coarse sediment transfer from metal mines to channels. The nature and timing of mining impacts on river channels depends on the locations of the mines within the catchment; only those close to the channel network being likely to have contributed sediment. The extent to which sediment inputs reflected the level of ore production of a given mine, the nature of post extraction processing on site, or differing extraction techniques, all require further investigation. The onset of sedimentation within Weardale prior to the peak of metal production at the end of the

nineteenth century suggests that sediment generation was not governed simply by the productivity of mines; mining technique was also important. High ore output at the end of the nineteenth century represented improvements in the efficiency of ore extraction, not simply more mining.

Hushing for example, was a widely employed mining practice in the North Pennines during the eighteenth and early nineteenth century, but ceased by the late 1840s (Cranstone, 1992). Prior to this study, Black Burn in the South Tyne catchment provided the only clear example of channel transformation downstream from a hush; here the channel was transformed by the impact of coarse sediment delivery (Macklin, 1997a). In this study the extensive gravel bars found in the Ireshope and Bollihope study reaches appear to be a result of hushing. Extensive bars also occurred downstream of hushes in the Burnhope and Killhope catchments, although in these instances a combination of channel confinement and high gradient appears to have prevented the formation of sedimentation zones (Figure 4.5). In mines where hushing was not practiced the total ore production of individual mines offers the only insight into the relative impacts of different mines in the catchment (Figure 4.9b). Production records demonstrate pronounced variation in mining intensities between mines and indicate many of the most productive mines were located close to the trunk channel of the tributary catchments and may have delivered considerable quantities of sediment to the river network, perhaps during initial excavations (Figure 4.9). Similarly the practice of hushing meant that considerable volumes of sediment were directed down-slope into the river valleys.

The introduction of fine metal contaminated sediment has been linked to increases in gravel bar extents some distance downstream from mines due to the destabilisation of riverbanks and vegetation retardation (Lewin and Macklin, 1987). Such destabilisation will have increased the sensitivity of the river channels to flood events and hindered vegetation colonisation of flood deposits. In Weardale much of the metal mining was concentrated in the tributary catchments (Figure 4.9), however the downstream transfer of sediment to the trunk channel will have contributed to the extensive gravel-bars of the sedimentation zones during the nineteenth century. In the neighbouring Tyne catchment increases in gravel bar areas during the late nineteenth century have been associated with metal mining (Aspinal and Macklin, 1985; Macklin and Lewin, 1989 and Passmore et al., 1993). In catchments where sediment supply was augmented by mining activity, channel incision during the late nineteenth century was delayed (Higgitt et al., 2001).

The transfer of sediment through mined catchments has been observed in South Tynedale (Macklin, 1986; Macklin and Lewin, 1989). On a larger scale Knighton (1989) described the downstream migration of sedimentation as a result of tin mining in Tasmanian catchments. Pulses of sedimentation such as this, and the resulting transformation of river channels, are considered to represent the passage of large sediment slugs (Nicholas et al, 1995). The sedimentation patterns in Weardale, discussed in chapter 4 and confirmed by chapters 5 and 6, indicate that a pulse of sedimentation migrated downstream from the upper catchment (tributaries) to the lower catchment. Beginning in the early nineteenth century in the tributaries, sedimentation occurred at Brotherlee (upper trunk channel) prior to 1841 before beginning at Wolsingham and Harperley (lower catchment) between 1844 and 1856. The sedimentation pattern patterns recorded in Weardale reflect the concentration of mining activities in the upper catchment. Indeed, both the most productive mines and those that employed hushing are located in the upper catchment (Figure 4.9); the history of channel planform change reflects this. Had the arrangement of metal mines been more uniform in the catchment, or if mining was not an important control on sedimentation patterns, this trend may not have been as pronounced. Channel changes would have been more synchronous. The importance of metal mining is also demonstrated by the lack of significant channel activity along Waskerley Beck, where no mining was carried out (Figure 4.9). At present, with the exception of Waskerly Beck, lead and zinc contamination in fluvial sediments in Weardale remains high throughout Weardale (Lord and Morgan, 2003).

Metal mining can be regarded as a primer for channel planform change due to the instability of the banks and bars following metal contamination (Brewer and Lewin, 1998). The impact of the large floods during the nineteenth century (Figure 8.3 and 8.5) will have been increased due to the sensitisation of the river channel. The coincidence of flooding with the introduction of mining waste is likely to have been critical to the development of a pulse of sediment through Weardale. Gravel-bed rivers are competence-limited and so the occurrence of large floods is essential for the transfer of sediment through the catchment. Indeed, the onset of channel planform transformation in the nearby Nent catchment occurred due to a combination of mining and flooding (Macklin, 1986). In locations relatively distant from metal mines (such as Wolsingham) channel transformation will therefore have been primed by mining waste but triggered by floods. The close relationship between the catchment flood history and the behaviour of the river channels throughout the historic period (1841-1991), in particular the decline in the extent of gravel bars

during the twentieth century, emphasises the importance of flooding in controlling channel planform change.

8.3.2 *Reach-scale influences*

8.3.2.1 Gravel extraction

Commercial gravel extraction operations were conducted along the Wolsingham (1945-1960) and Harperley Park reaches (1960-1968). The nature of the channel planform at Low Bat during 1971 (Figure 6.9) indicates that gravel extraction operations were also undertaken in this reach. As described in Chapter 6, the impact of these operations on the river channel during and immediately following the operations depended upon the method of extraction employed. The excavation of pits within the channel bed and the episodic re-routing of the wetted channel (as at Wolsingham) promoted sediment release and downstream sedimentation. In addition, localised bed lowering causes knick point development. The upstream migration of knick points due to gravel extraction operations and their effect on channel stability is well documented (Kondolf and Swanson, 1993; Sear and Archer, 1998). In Weardale, however, future upstream migration of the knick point, following the destruction of the bed-check weirs, is likely to be limited due to the outcropping of bedrock in the riverbed upstream.

While the excavation of straight channels deliberately graded to merge into the bed upstream at Harperley Park prevented immediate channel stability problems, recent field evidence indicates that renewed sedimentation has begun to occur in the reach and is promoting renewed bank erosion (Figure 8.7). Bar formation such as this is common in artificially straightened channels (Brookes, 1987), indeed evidence suggests that channel straightening at Harperley Park during the nineteenth century was also followed by renewed sedimentation within the channel and bar development (section 6.3.8). Perhaps one of the finest examples of bar development following channel straightening is described by Lewin (1976) on the River Ystwyth in Wales. In this example, bar and meander development reached an advanced stage within 6 months of straightening. Such rapid readjustment did not occur at Harperley Park, as bend re-development was not evident in 1991 some 23 years after straightening (Figure 6.26). Indeed, it is now 35 years since extraction operations ceased along this section of river. There are a number of possible explanations for this delay in sedimentation. First, the enlarged channel at the Wolsingham extraction site,

Figure 8.7 Photographs illustrating the impact of recent sedimentation in the Harperley Park reach: (a) view showing recent bar sediments and resulting bank erosion along the right bank; (b) view looking upstream towards the bar illustrating resultant bend development. The bar is located in the middle reaches of the straightened section in the location of bend 2 on Figure 6.26. Note the falling trees in the back ground indicating recent bank erosion.

a



b



upstream, may have trapped sediment moving down the trunk channel during the latter half of the twentieth century; indeed, sedimentation in the lower section of the Wolsingham reach suggests this. Secondly, the relatively large post-extraction channel containing no gravel bars may have had sufficient capacity to absorb initial sedimentation without an erosional response, although aerial photographs indicate little sedimentation had occurred by 1991. Finally, the late twentieth century was characterised by relatively low flood frequencies and magnitudes, which will have limited sediment transfer to the reach. Recent sedimentation was coincident with the 1995 flood, the largest recorded in Weardale during the last 40 years (Figure 8.5b), indicating that earlier low flood magnitudes promoted channel stability.

To date the wider importance of gravel extraction remains to be fully appreciated in the context of British rivers (Newson, 2003). This may be because former extraction sites are often difficult to identify in the field. In the years following the cessation of extraction in Weardale, exposed bars became colonised by vegetation and the wetted channel became single thread. Three decades after extraction, reaches are barely distinguishable from the surrounding non-extracted reaches. This raises the issue of equifinality. Over a timescale of several decades both gravel-extraction and declining flood frequencies can result in near identical channel planform structures. The only evidence of past gravel extraction being unusually straight channels and the presence of bed-check weirs.

Relatively few studies have focused on the impact of gravel extraction as an agent of channel change in British gravel-bed rivers. However these findings and a recent study in the Tyne catchment (Archer, 2003) suggest that the importance of gravel extraction operations has been seriously underestimated. Channel incision during the twentieth century attributed to an increase in flood frequency and magnitude (not detected in the Wear catchment), appears in fact to have been caused by widespread gravel extraction operations (Archer, 2003). The delayed response of extracted reaches to variations in sediment delivery and flood frequency evident at Harperley Park, suggests that such sites can become locations of renewed channel planform instability despite the passage of decades since the cessation of extraction.

8.3.2.2 Channelization

Channelization has been widespread in British Rivers (Brookes, 1987). As discussed in chapter 2, channelisation can lead to downstream channel instability (Leeks et al., 1988). Within this study only two examples of channelisation were recorded (Harperley Park c.1844 and Trout Beck Ford c.1950). Despite representing only a very localised cause of channel change, both led to downstream sedimentation and temporary channel instability. Significantly, instances of channelisation and associated channel instability appear to coincide with flood events. The channel instability recorded at Harperley Park during the early 1850s was coincident with bend removal and the channel changes appear to be consistent with the types of channel response described downstream of such interference. However, the arrival of a pulse of sedimentation and associated large floods, together with mining contamination, could equally have caused this channel destabilisation. Indeed, the extent and persistence of the channel changes in the subsequent decades suggests flooding and sediment delivery were important. The importance of sediment availability and flood frequency and magnitude in determining the nature of channel response to channelisation is illustrated by the Harperley Park reach. Channel re-adjustment following straightening during the mid-twentieth century was very gradual in comparison to the rapid response during the nineteenth century (Chapter 6). Future increases in flood frequency and magnitude are likely to lead to further channel changes in this reach and potentially the re-establishment of a sinuous channel planform, similar to that recorded by Lewin (1976).

8.3.2.3 Local land use practices

Additional reach-scale influences are known to have been important in Weardale, each with capacity to alter the channel planform to some degree; these are quarrying, forestry and reservoirs. Evidence for channel change due to quarrying (sediment delivery to the river channel leading to channel division) was only observed along the Bollihope reach (Figure 6.6). Planform changes did not occur in response to either recent afforestation in the Wellhope catchment or following reservoir construction (Burnhope and Waskerley Beck). Several studies demonstrate the detrimental downstream effects of reservoir impoundments, as summarised in chapter 3. The most significant of these is caused by a reduction in sediment delivery downstream. Such a decline might have been expected particularly from the Burnhope catchment, however the reservoir here was built during the 1930s after the main pulse of sediment through the catchment. Sedimentation rates in the Burnhope

reservoir indicate limited coarse sediment deposition since impoundment implying that sediment delivery was already limited prior to reservoir construction (Holliday, 2003). The reservoir will therefore have had little impact on downstream sediment transfer, or channel planform. It is difficult to assess the impact of the Waskerley and Tunstall Reservoirs as the reaches downstream are either confined or did not show significant bars prior to reservoir construction. The lack of metal mines and the relatively small upstream catchment area of Waskerley Beck suggest sediment transfer rates would have been low prior to reservoir construction, resulting in a limited impact. Finally, the impact of these reservoirs on the hydrology of the catchment is difficult to ascertain; although they will have reduced local flood magnitudes, their upstream catchments constitute a relatively small portion of the total catchment area (Table 8.3). As such the overall impact of these reservoirs on the hydrology of the catchment is low.

Table 8.3 Area of catchment upstream of Weardale reservoirs. *Includes the catchment of Waskerley Reservoir which lies in the headwaters above Tunstall.

Reservoir	Area km ²	% of total catchment area impounded
Burnhope	16	5
Waskerley	4	1
Tunstall*	23*	7*
<hr/>		
Total catchment	322	12

8.4. Implications – controls on planform structure in gravel-bed rivers

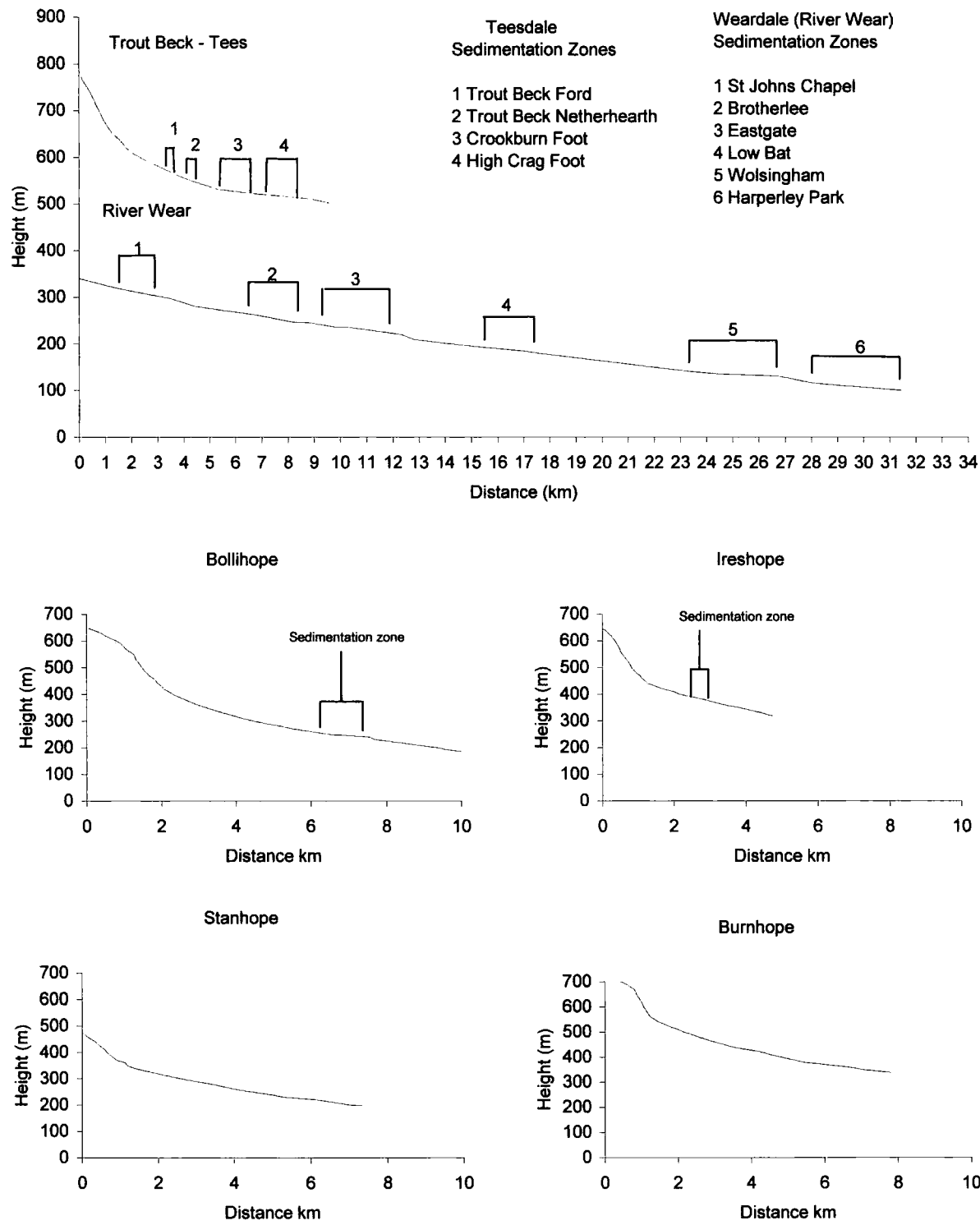
The river channels of Weardale between 1841 and 1951, and upper Teesdale between 1856 and present, show a channel planform structure characteristic of wandering gravel-bed rivers as defined by Church (1983). The channels are characterised by laterally unstable frequently braided reaches (sedimentation zones), separated by laterally stable single thread channels. Functionally these reaches have acted as storage reaches and transfer reaches respectively. The distinction between these reaches is governed by the degree of lateral confinement, which is low in sedimentation zones. In Weardale and upper Teesdale sedimentation zones are more numerous along the trunk channels while the tributaries are relatively steep and confined. The presence of storage reaches delays the transfer of sediment through catchments and explains the delay in sedimentation in the lower reaches of the trunk

channel during the nineteenth century. With the exception of the Ireshope, Bollihope and Swinhope catchments, there is relatively little sediment storage capacity in the tributary channel network of Weardale (and upper Teesdale) and this will have allowed efficient sediment transfer from tributaries to the trunk channel, perhaps over the order of decades (Newson and Leeks, 1987).

The distribution of sedimentation zones is controlled by both valley gradient and lateral confinement. For example, both the Ireshope and Bollihope sedimentation zones are located where both the valley gradient and degree of lateral confinement decline substantially (Figure 8.8a). Similarly, in other tributaries gravel bars are most extensive downstream of reduction in valley slope. Along Trout Beck, in upper Teesdale (Figure 8.8b), the sedimentation zones are not coincident with substantial reductions in gradient; rather the sedimentation zones appear to have been encouraged by a decline in lateral confinement. Although the persistence of channel planform activity in these reaches reflects their relatively steep gradient. The relatively shallow channel gradient of the River Wear and River Tees (Figure 8.8b) will have produced a relatively constant rate of sediment transfer. However, the alternating pattern between confined (mostly bedrock) and unconfined (alluvial) reaches has resulted in the alternation of transfer and storage reaches, and as such discontinuous sediment transfer. In trunk channel settings lateral confinement provides the key geological control on channel planform behaviour.

The change of the channel planform in Weardale from wandering to single thread, following a reduction in flood frequency and magnitude and the cessation of metal mining, indicates the sensitivity of these reaches to sediment supply and discharge regime. In Teesdale, however, despite a similar climate, land use history and channel setting (gradient and degree of confinement), the localised channel division persists in the form of large vegetated islands. The majority of the islands appear to have been stable throughout the historic period. The long-term stability of these islands (continuous vegetation cover and well developed soil) makes these features essentially detached portions of floodplain rather than mid-channel bars. Such islands cannot be considered as components of the active channel. In Weardale such vegetated islands were not present during the last 150 years. However, during early to mid twentieth century the Low Bat, Wolsingham and Harperley Park reaches all had mid-channel bars showing evidence of stabilisation through vegetation

Figure 8.8 Long profiles of (a) the River Wear and Upper Tees study channels and (b) selected Weardale tributaries.

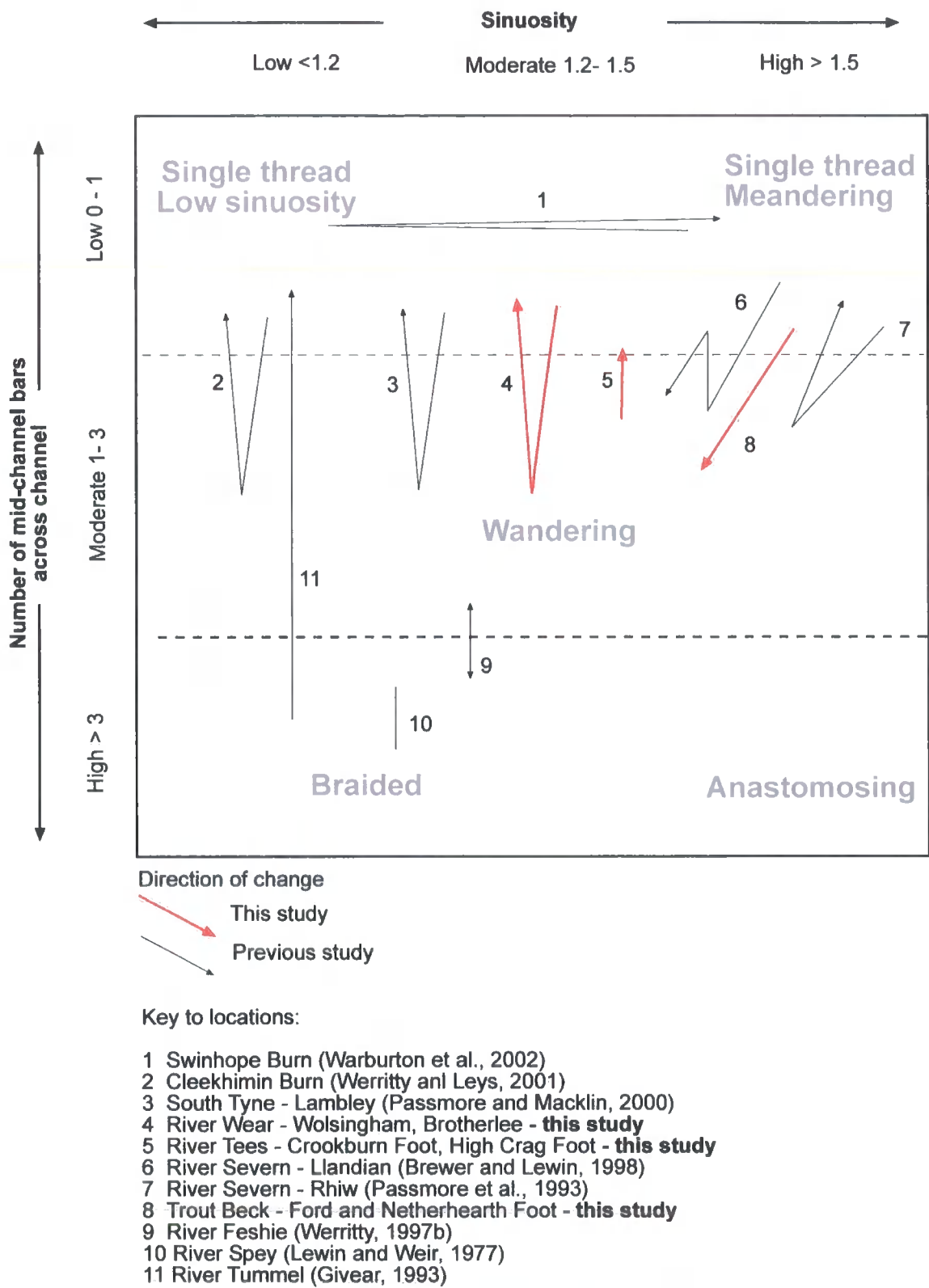


colonisation (chapter 6). Determining whether or not these mid-channel features can be considered components of the active channel has implications for sediment budgets. This is particularly significant when attempting to determine the impact of gravel extraction (Section 6.4.1.1). It is possible that, had gravel extraction not been carried out in Weardale, the River Wear may have developed islands similar to those in upper Teesdale.

The stabilisation of mid-channel bars in the sedimentation zones of wandering gravel-bed rivers has been referred to as planform 'freezing' (Brewer and Lewin, 1998). In these circumstances the river channel has stabilised, but owing to their history of planform change such reaches are likely to become the sites of renewed channel instability should flood frequency and magnitude increase (Brewer and Lewin, 1998). In Weardale, in contrast to upper Teesdale, within-channel gravel-extraction has resulted in a fundamental readjustment of channel planform. However the evidence from Harperley Park suggests that extracted reaches remain sensitive to increases in sediment delivery.

The loss of active sedimentation zones in the Wear and Tees catchments means these rivers cannot be regarded as having contemporary wandering planforms. However some British upland rivers can still be referred to as wandering gravel-bed rivers, particularly those in the Scottish Highlands which lie within mountainous catchments. Nevertheless the majority of British gravel-bed rivers have experienced historic channel planform change. As discussed in chapter 2, channel planform must be regarded as a continuum. The direction of recent changes in channel planform in selected British gravel-bed rivers is illustrated in Figure 8.9. The rivers of the British uplands have shown pronounced variation in their channel planform history. This reflects the importance of the individual setting of rivers and also their modification by anthropogenic activities. Those channels considered in this study (coloured red on Figure 8.9) show clear variation in their behaviour due to local factors. This illustrates the difficulty in extrapolating the effects of catchment and reach-scale controls on channel planform made in one catchment to others, without first establishing their context (location, structure and land use histories). British upland rivers cannot necessarily be regarded as having shared histories or similar responses to disturbance. This has important implications for river management strategies, which must establish how a given river has responded in the past to determine the likely response to future climate changes.

Figure 8.9 Channel change histories of selected British gravel-bed rivers over approximately the last 200 years, including those in this study.



Given the variability of the climate during the last 200 years and resulting changes in river channel behaviour, Figure 8.9 illustrates the potential for adjustment in river channel planform should changes in climate and land use occur. Contemporary wandering gravel-bed rivers tend to be those where sediment delivery rates are high and the discharge regime is flashy and subject to large floods. These conditions were more prevalent in the British uplands during the nineteenth century than present. Many presently single thread channels were once wandering gravel-bed rivers and as such may be sensitive to future changes in climate and land use. This study has demonstrated that increases in sediment supply and flood frequency and magnitude (which can be interlinked) can lead to relatively rapid (decades) changes in channel planform. This can affect relatively large channel lengths (30 km or more) and can influence channel planform over a hundred years or more. Similarly localised changes such as channel modifications can lead to channel adjustment, but this tends to be spatially and temporally limited (around 3 km over decades).

Determining the likely impact of future climatic change on geomorphological systems is becoming an important research agenda (Jones, 1993). In the context of the fluvial system efforts have focused on attempts to determine likely changes in flood frequency and magnitude (Newson and Lewin, 1991; Beven, 1993). Yet in Britain considerable uncertainties remain as to likely changes in the nature of riverine flooding, largely due to the complexity of the British climate system and the sensitivity of flooding to variation in rainfall event characteristics (Newson and Lewin, 1991). Furthermore, studies which have attempted to model the impact of climatic change on rainfall events, based on a range of differing assumptions about the generation of rainstorms and resulting runoff, do not provide appropriate representations of reality (Beven, 1989). Generally the frequency of flood producing rainfall is expected to increase in winter and spring (Beven, 1993) particularly in northern Britain, while the south will experience drier summers (Newson and Lewin, 1991). In the summer months the incidence of convective storms, such as that which generated the flood in Upper Teesdale on 30 July 2002, are also expected to increase in magnitude and frequency (Beven, 1993).

Climatic change is therefore likely to increase the magnitude and frequency of flooding in British upland rivers. The flood record for the River Wear at Sunderland Bridge (Figure 8.5c) reveals a trend for increasing flood frequency and magnitude since the early 1990s, with a particular cluster of floods during 2000, which may represent the flood response to climatic change predicted in the 1990s. However, the

highest magnitude floods at around $400 \text{ m}^3\text{s}^{-1}$ are not as extreme as the floods of the nineteenth century with flood peaks in excess of $500 \text{ m}^3\text{s}^{-1}$ (Figure 8.5a). Additionally, these events are not all detected in the Weardale flood record from Stanhope (Figure 8.5b); entire catchment floods tend to be those over $500 \text{ m}^3\text{s}^{-1}$ at Durham. Should the recent trend for increasing flood frequency and magnitude continue toward a situation similar to the mid nineteenth century, significant changes in channel planform behaviour might be expected in Weardale.

Channel behaviour in Weardale during the nineteenth century reflected the interaction of catchment land use (metal mining) and high magnitude flooding. The legacy of the Little Ice Age also appears to have resulted in high sediment availability in the catchment during the nineteenth century. An increase in flood magnitude alone may not necessarily be sufficient to induce significant channel planform change. Channel planform change in gravel-bed rivers is dependant on sediment supply, and this may not increase enough to promote channel planform change. Those rivers that have shown a planform tendency towards a single thread channel (Figure 8.9) over the historic period (indicative of declining sediment supply and flood magnitudes) are unlikely to be subject to rapid channel transformation. However, a period of sustained high magnitude flooding and frequent convective storms may eventually deliver sufficient quantities of sediment to these trunk channels and promote channel planform destabilisation. In this eventuality, reaches subject to historic planform change will be those most prone to future channel instability, due to the abundance of re-workable material in their banks (former bars) and lack of lateral confinement. Those rivers with contemporary wandering channel planforms, indicative of high sediment supply and a flashy flood regime, are likely to be the most sensitive to climatic change.

Where river channels have been modified by anthropogenic activities such as gravel extraction, increases in sediment delivery and flood frequency may be sufficient to induce planform instability. Rivers that have been artificially straightened are likely to be most vulnerable. Gravel extraction was an important cause of channel planform change in during the mid-twentieth century in lower Weardale. Field evidence from Harperley Park indicates that renewed sedimentation has begun in the extracted reach, in response to the flood of 1995 (Figure 8.5b). This reach provides an indication of channel response to changing flood frequency. Here sedimentation along the outer margin of a lateral bar has begun to cause bank erosion along the outer bank of the channel (Figure 8.7). Historically this reach was characterised by a

wandering channel planform and it appears that, should flood frequency and magnitude increase, the river channel can be expected to change towards a wandering planform. Understanding the historic context of a river channel and the nature of anthropogenic changes therefore provides the key to determining the likely nature of future channel planform change in response to climate change.

8.5 Conclusion

This study has demonstrated that catchment-scale (climate and metal mining) and reach-scale (gravel extraction and channelization) factors influenced river channel behaviour in Weardale and upper Teesdale over the historic period (Figure 8.10). Of these influences, river channel planform appears to have been determined by changes in flood frequency and magnitude augmented by variations in sediment delivery, principally as a result of metal mining. During the nineteenth century, climate and metal mining combined to produce a phase of sedimentation, which migrated downstream promoting the development of sedimentation zones through increases in gravel bar area. Following a decline in flood frequency and magnitude and the cessation of metal mining, the extent of gravel within these sedimentation zones began to decline through vegetation colonisation. Initially localised sediment re-working occurred during occasional floods, due to the relatively slow vegetation colonisation of gravel bars which was impeded by metal contamination. However by the middle and late twentieth century, bar extents declined throughout the catchment. By the end of the twentieth century the extent of the gravel area within the channel had declined to such an extent that all the sedimentation zones became stabilised. In the lower catchment, however, the decline in the activity of the river channels was initially delayed due to gravel extraction but following the cessation of extraction the river channels stabilised, adopting a planform similar to the other stabilised sedimentation zones in the catchment.

The behaviour of the Weardale and Teesdale catchments appears to be related to the same general processes (although there was no detectable gravel-extraction in upper Teesdale). The functioning of these catchments can be summarised using a conceptual sediment budget to demonstrate the key process interactions (Figure 8.11). The sediment budget has been produced for the years 1860 and 1960, to demonstrate the changes in catchment behaviour over 100 years. In 1850 the high flood frequency and magnitude led to effective coupling within the catchment, leading

Figure 8.10 Summary diagram comparing catchment flood history, climate circulation and land use (including channel interference and resulting channel response).

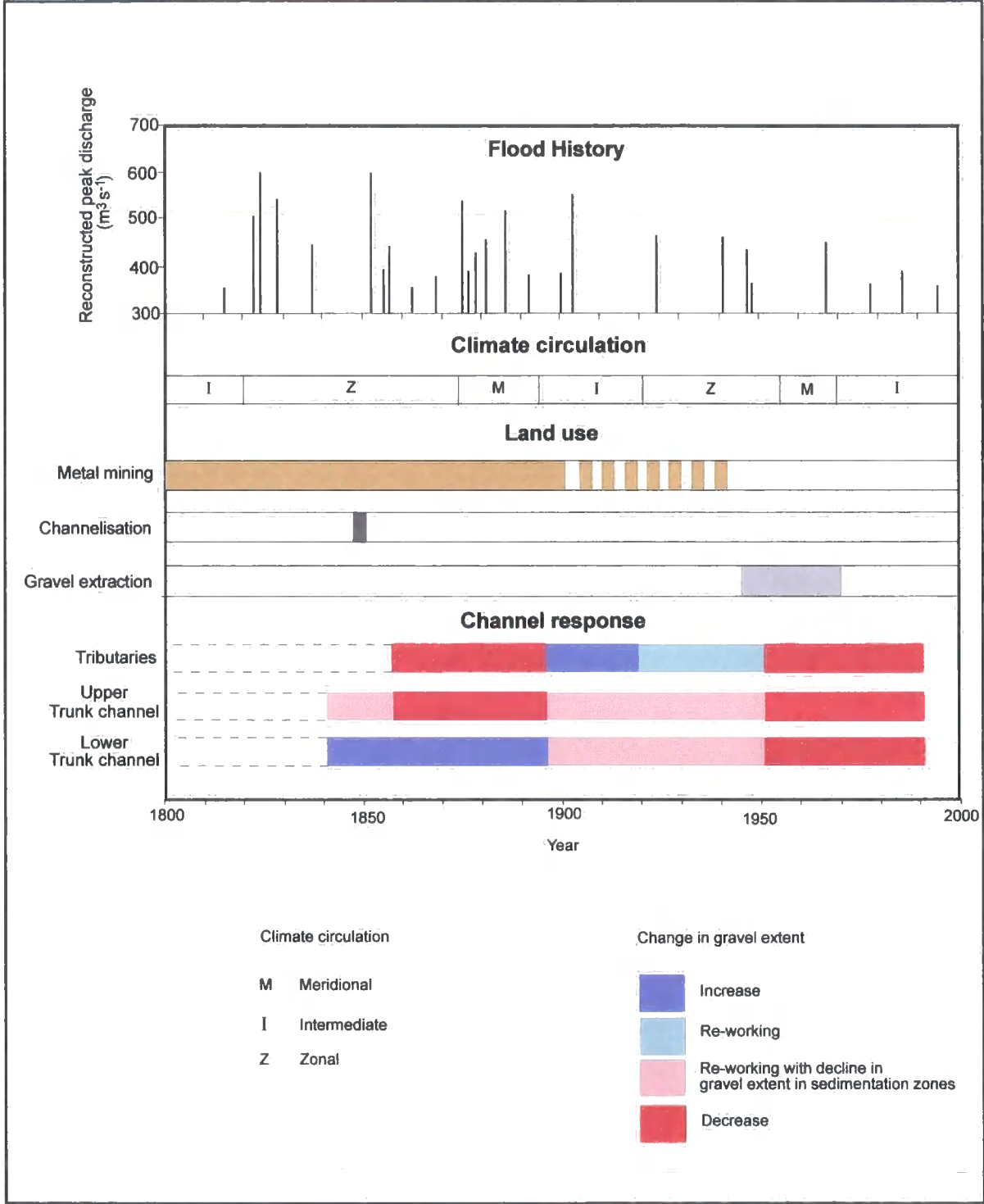
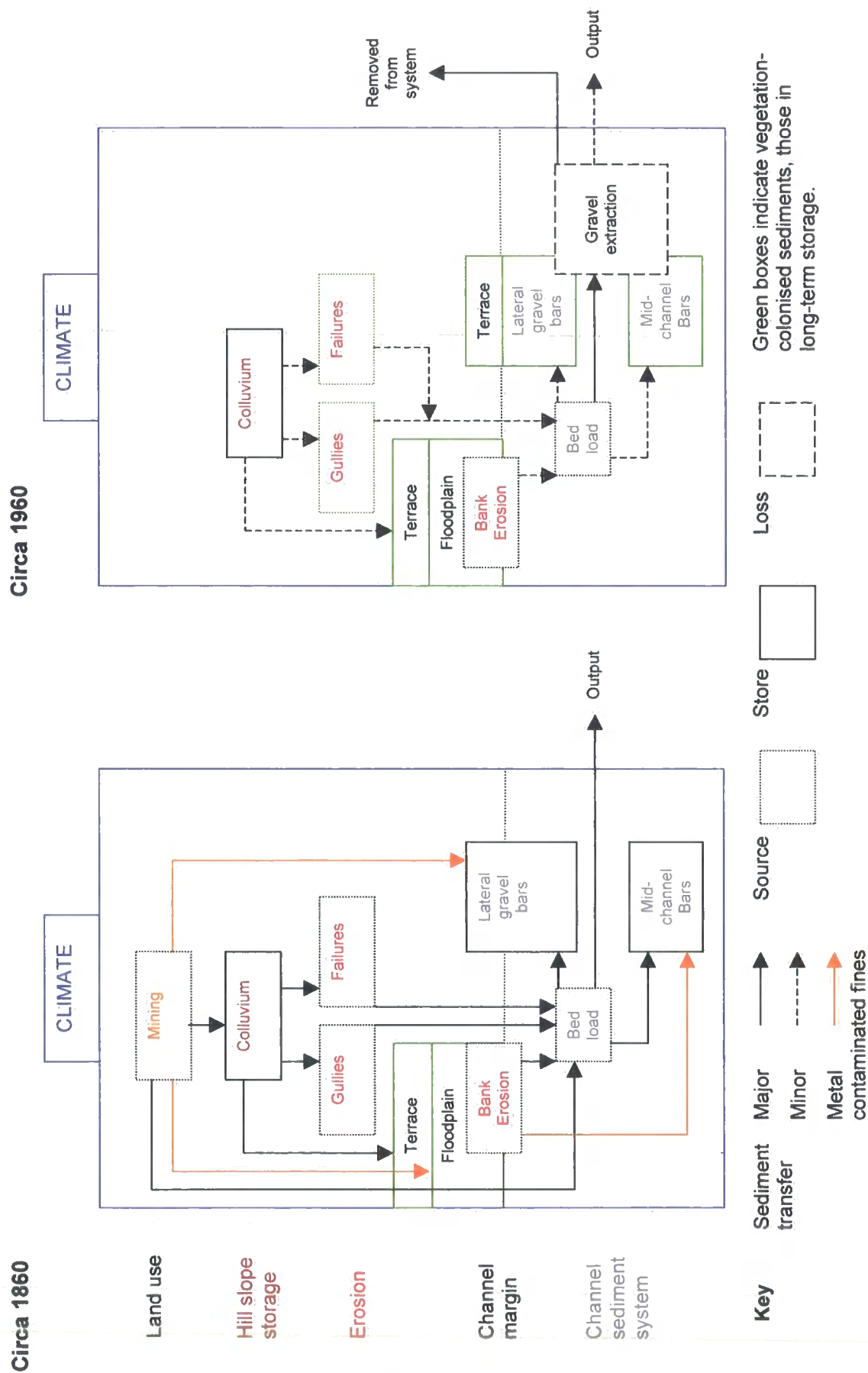


Figure 8.11 Conceptual sediment budgets for sediment supply and channel adjustment in the North Pennines during 1860 and 1991.



to active sediment transfers through the catchment. Metal mines were active during this period and contributed sediment both directly to the river channels and also to the surrounding hill slope. Much of this sediment was stored as colluvium, but gullies and slope failures ensured some sediment was transferred to the channel network. The efficiency of slope processes (landslides and gullying) was primarily a legacy of the Little Ice Age. Material was also delivered to the river channel through more effective bank erosion during the large flood events. The efficient delivery of sediment to the channel network encouraged the development of both mid-channel bars and large lateral bars within the channel. This bar growth transformed the river channels from single thread to wandering planforms.

By 1960, however, the decline in frequency of high magnitude floods led to a reduction in coupling within the catchment. This, and the decline in metal mining, reduced the amount of sediment delivered to the river channel network. In addition, slope processes such as gullying were beginning to decline, with vegetation colonisation reducing the amount of sediment delivered to the channel network from the slopes. The reduction in sediment delivery to the river channel, combined with the decline in flooding, promoted gravel bar stabilisation through vegetation colonisation. However, in the lower catchment in particular, large volumes of sediment were removed by gravel extraction operations. The combination of intensive gravel extraction and a decline in sediment generation resulted in the sediment budget of the catchment becoming negative. The impact of this on the channels was a simplification of planform through a reduction in bar extents and in particular the loss of mid-channel bars.

Climatologically induced increases in flood frequency and magnitude are likely to increase coupling between the components of the sediment budget, leading to more efficient sediment transfers. Given the nature of the historic flood record and catchment behaviour in Weardale, it is unlikely that significant channel changes will occur in Weardale until flood magnitudes at Durham are regularly exceeding $500 \text{ m}^3\text{s}^{-1}$. The absence of metal mining, low antecedent flood frequencies and magnitude and mild annual temperatures (as compared to the Little Ice Age) mean that the response of river channels is not likely to be as dramatic as during the nineteenth century as limited winter freeze-thaw activity in the upper catchment means slopes are less likely to contribute sediment to the headwater streams. Nevertheless the locations of channel instability are likely to be those that were active during the nineteenth century.

Chapter 9 Conclusion

9.1. Summary of research

This study has provided one of the most comprehensive evaluations of the nature of and controls on channel planform change over the last 150 years in the British uplands. The research has focused on determining the nature and causes of historic channel planform change in the upland catchment of the River Wear in Weardale, County Durham. The study adopted a nested research framework, including a catchment scale appraisal of the extent and distribution of river channel changes over the period 1856-1991. This revealed a pronounced variation in the magnitude of channel planform changes throughout the catchment, the most significant changes being in sedimentation zones. Nested within this broad framework, detailed reconstructions of the channel width structure were made along the trunk channel of the catchment (31 km) for the years 1856, 1896, 1951 and 1991. This confirmed the significance of the sedimentation zones as the primary sites of channel planform change. Finally, based on a combination of the catchment scale analysis and the trunk channel investigations, eight study reaches were selected for detailed analysis. These reach scale investigations involved the reconstruction of change in channel planform over historic time. Locally these investigations benefited from additional sources of planform information, such as nineteenth century plans and aerial photography from the 1970s.

In order to assess the significance of the results from Weardale, an additional study was undertaken in the headwaters of the River Tees, in upper Teesdale. This involved measurement of the contemporary channel width structure of the trunk channel of the catchment over a total channel length of 5.9 km. Comparisons between the trunk channel of this catchment and the River Wear revealed that the upper Tees and Trout Beck have a channel planform structure, characterised by discrete sedimentation zones, similar to those which were present along the River Wear during the mid to late nineteenth and early twentieth centuries. In addition, planform changes were reconstructed along four study reaches located on the trunk channel. Comparisons between these historic channel changes and the impact of a large flood event, which occurred during July 2002, were made.

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A major benefit of this combined catchment and reach-scale approach, coupled with the additional analysis from upper Teesdale, is that it allowed a wide range of potential controls on river channel planform to be examined. Processes ranged from those operating at the scale of the entire catchment, such as climate and large-scale land use change (primarily metal mining), to relatively localised controls such as gravel extraction operations and channel engineering. In addition the wide spatial scale of the analysis enabled a range of differing channel settings to be investigated. This enabled an appreciation of the role of catchment geomorphology in determining the intensity and duration of channel planform change. The contrast in catchment setting and structure between Weardale and Teesdale proved to be particularly significant. The findings demonstrate that over century timescales reaches can reflect catchment-scale changes (climate and land use), but can be subject to local influences (gravel extraction) that can determine channel planform over decades. The degree to which one site is representative of others in same catchment or region is governed by both the timescale of enquiry and the geological and geomorphological setting of the channel.

9.2. Major findings

1. *A decline in flood frequency and magnitude since the beginning of the Twentieth Century was coincident with a decline in the extent of gravel bars along the trunk channel of the River Wear.*

Following a phase of localised channel planform re-working during the period 1896-1919, associated with relatively little change in the extent of active gravel bars a period of bar stabilisation began following 1919, involving the vegetation colonisation of gravel bars. While localised increases in gravel area were recorded between 1919 and 1951, the decline in gravel extent was clustered in sedimentation zones; this appears to have begun as early as 1896. Between 1951 and 1991 however the entire catchment showed a decline in the extent of gravel bars. This decline in bar extent was coincident with a progressive decrease in flood frequency and magnitude during the twentieth century. This does not appear to have been associated with widespread channel incision, in contrast to the South Tyne (Rumsby and Macklin, 1994, 1996). Rather the decline in flood magnitude led to the inability of the river to re-work the extensive bars of the late nineteenth century. The contrast in channel morphology resulting from this change along the trunk channel was clearly revealed by the time-series

analysis. This showed a switch from the long wide sedimentation zones and persistent narrow transfer reaches to a pattern dominated by frequent, but small gravel bars and little persistence in wide and narrow reaches. While a similar decline in the extent of active bars was also recorded in the upper Teesdale catchment, locally high channel widths were maintained due to the persistence of flow division around large (but now vegetated) mid-channel bars.

2. Anthropogenic channel modifications exert a major local impact on channel morphology and have been particularly significant during the late twentieth century.

Direct anthropogenic channel modification took the form of both gravel extraction operations (Brotherlee 1968, Low Bat c. 1970, Wolsingham 1945-1960 and Harperley 1960-1968) and alterations to channel routing, specifically bend removal (Harperley c. 1845 and Trout Beck Ford c. 1950). Both forms of channel modification led to local channel instability at the site of interference and downstream. Examples of bend removal were coincident with persistent changes to channel planform, which was enhanced by the passage of large flood events. However, the extent of channel instability associated with alluvial gravel extraction was determined by the extraction technique employed. The reaches affected by dragline gravel extraction and the excavation of a new channel (Low Bat and Harperley) appeared to stabilise relatively rapidly following extraction. The Wolsingham site, in which excavations involved pit excavations and repeated switching of flow routing was characterised by unstable downstream sedimentation and channel braiding for over two decades following the cessation of extraction. However, in the longer term (40 years) all the sites affected by gravel extraction adopted a laterally stable single-thread channel planform characterised by infrequent gravel bars.

The contrasting channel-width-series structure of the River Wear and Tees during the 1990s is likely to have been significantly influenced by the gravel extraction operations. The Low Bat, Wolsingham and Harperley Park reaches were all characterised, during the first half of the twentieth century, by large vegetating mid-channel bars. These were removed by gravel extraction operations (of both methods) and in the case of Low Bat and Harperley a new single channel excavated by the gravel extractors through the centre of the former mid-channel bars.

Knowledge of past channel interference, such as gravel extraction and channelisation, is critical for understanding the origin of contemporary river channel planform. Perhaps more significantly, however, channel interference can lead to longer-term problems of channel instability, which may be arrested by management (such as bed-check weirs). However, predictions of increased flood magnitudes and frequency (together with the ageing nature of channel stabilisation measures) mean that problems due to river erosion may increase in future decades. Importantly however, the context of the river channel is critical for determining future changes; for example, a solid rock bed may reduce the upstream migration of instability, such as knick points (Wolsingham reach).

3. *The extensive gravel bars, which dominated the Weardale catchment during the nineteenth and early twentieth centuries, were formed when a pulse of sediment migrated through the catchment during the mid-nineteenth century.*

The pattern of sedimentation revealed by the catchment scale analysis demonstrated that a phase of sedimentation occurred in the lower reach of the catchment between 1844 and 1856 and continued, albeit at a reduced rate, between 1856 and 1896. Evidence from Brotherlee suggests that, in the upper reaches of the catchment, decline in the extent of gravel bars, which were widespread in the upper catchment between 1856 and 1896, began during the period 1841-1856. The nature of channel planform changes in the catchment indicate the downstream migration of a sediment slug. Over the period 1844-1856 the lower reaches of the catchment were destabilised and sedimentation increased, resulting in the development of the sedimentation zones. Smaller pulses of sedimentation between 1856 and 1896 resulted in some localised increases in gravel bar extents in the lower reaches.

4. *The initiation and downstream translation of this pulse of nineteenth century sedimentation was caused by high magnitude flooding during the nineteenth century augmented by an increase in sediment availability due to metal mining in the catchment*

Comparing channel planform change in Weardale, during for the mid to late nineteenth century, with those produced by the flood of 2002 in upper Teesdale revealed many similarities in the nature of the channel changes. This included localised gravel spreads onto the riverbanks (Low Bat), fresh gravel deposits within abandoned channels (Eastgate), localised channel division suggestive of avulsion and out-of-channel flow (Wolsingham). In addition, archive documentary

descriptions of the impact of late nineteenth century flood events in Weardale correspond well to channel changes recorded from historic maps. Particularly good correspondence was found for the Wolsingham reach.

Evidence for the enhanced sediment delivery to the river network during the late nineteenth century was provided by the coincidence of extensive gravel bars and channel instability downstream from metal mines, in particular hushes in the Ireshope and Bollihope catchments. Extensive gravel bars were also observed within the river channel downstream of mine workings in the Burnhope and Killhope catchments. Generally, changes in gravel bar areas were more frequent and extensive in those reaches affected by significant metal mining than those where mining was not practiced (Waskerley Beck), or less intensive, such as Westernhope Burn and Wellhope Burn. Previous investigations conducted in the Swinhope catchment revealed a period of channel planform instability in this catchment which coincided with both an increase in flood frequency and magnitude and also the peak of metal mining in the catchment (Warburton et al., 2002). Significantly, a second phase of high flood frequency and magnitude during the late nineteenth century, and in the absence of metal mining, did not lead to renewed channel instability at Swinhope.

5. Large floods are the most important agents of planform change and lead to complex patterns of aggradation and incision.

The impact of flood events is strongly influenced by the quantity of available sediment and the setting of the channel. Alterations between narrow and wide reaches tend to result in variations in erosion and deposition. However, the extent of deposition is strongly determined by sediment delivery to the channel. For example, increased sediment availability due to mining and recent changes to climate appear to have resulted in greater flood deposition during the early nineteenth century, than the later nineteenth century. Nevertheless, both led to detectable changes in river channel planform, chiefly an increase in gravel-bar extent. Generalised whole-catchment flood histories should be treated with caution due to the interaction between differing synoptic situations and catchment structure. In upland settings it is preferable to consult specific historical accounts of flood events, as these give an indication of the relative magnitude of floods and their impact on the river channel.

9.3 Critique of methodology and suggestions for further research.

The nested research strategy adopted in Weardale and the comparative study in upper Teesdale has provided good evidence of the causes of channel planform change, in particular the significance of flooding. This approach enabled processes operating both at the scale of an entire catchment, and reach-scale, such as gravel-extraction, to be examined. The catchment scale approach has been particularly successful in leading subsequent, more focused investigations based on the magnitude of channel planform changes observed. The catchment scale analysis was restricted by the spatial and temporal coverage of archival maps and aerial photographs, of which only four years were available (1856, 1896, 1951 and 1991). The use of earlier maps to supplement the analysis was possible but only for discrete reaches of river channel. Fortunately these maps covered some of the most important sites, including an upper sedimentation zone and the two lower sedimentation zones. Investigations at the reach-scale enabled localised influences such as gravel extraction operations and local land use influences including quarrying to be investigated. Nesting these investigations within the catchment scale investigations enabled the most important reaches (in terms of channel planform change) to be targeted. The resolution offered at this scale means that reach-scale investigations are extremely useful for quantifying channel changes and identifying significant processes. Ideally, this level of detail should be applied to an entire catchment. Mapped within a GIS framework, the structure and changes in channel planform, specifically widths and bar areas, could be quantified with ease. However such an approach would be extremely time consuming. The nested research framework adopted here has enabled the key changes in channel planform to be identified and investigated in detail, and allowed process dominance to be determined.

This study has primarily focused on employing historical sources, principally maps and aerial photographs, for the reconstruction of channel behaviour, with support from field reconnaissance exercises. While this has given an understanding of the cause of historical change there are several details that remain to be quantified.

1. *The neighbouring Teesdale catchment (downstream from the upper Teesdale study site) has yet to be studied in this context.*

Investigations into river channel stability in the wider Teesdale catchment will enable a more complete understanding of the importance of metal mining (this catchment

was extensively mined) and climatic influences over the historic time to be appreciated in a wider context. This and longer-term investigations in this catchment will enhance our understanding of river channel behaviour at greater spatial and temporal scales.

2. *The importance of flood events could be potentially revealed in greater detail if geomorphological evidence from tributaries were used to reconstruct flood histories.*

Dating flood deposits such as boulders, berms and gravel spreads using lichenometry is widely employed, however it is seldom applied to multiple tributaries in the same catchment. A comprehensive study examining each of the major tributaries of the catchment will provide a detailed appreciation of the spatial variability of flood history and the degree of preservation of flood deposits. Such an analysis may allow the effects of localised storm-generated floods to be distinguished from catchment-scale flood events.

3. *The distribution of metal contaminants within Weardale remains to be determined for palaeochannel and floodplain settings. This will enable a detailed appraisal of the impact of metal mining to be made.*

Determining the variation in metal contaminants in formerly active bar surfaces (now incorporated into the floodplain) across a range of locations within the catchment (tributaries and trunk channel sedimentation zones in particular) will provide important quantification of the role of metal mining operations in influencing channel planform. Additionally this will enable the potential pollution hazard posed by these contaminants to be investigated, as has been investigated in mined catchments throughout the world (Chapter 2).

4. *The river terraces of the catchment require dating to provide an understanding of the behaviour of the river channel in the longer term.*

The current river channel is bound by a series of river terraces, crudely dated to the Pleistocene and Holocene by Moore (1994). These terraces, particularly the Holocene terraces, should be dated to establish the response of the river channel to longer-term climate and land-use influences. The river terraces of the neighbouring Tyne catchment (to the north) and nearby Yorkshire Dales catchments (to the south) have already been investigated in detail (Taylor and Macklin, 1997; Passmore and Macklin, 2000; Howard et al., 1998, 2000). Determining the age of these terraces and therefore longer-term behaviour of the river channel in Weardale will enhance our

understanding of the behaviour of river channels during the Holocene at the regional scale.

5. *The sediment transfers and channel changes identified in this thesis could be quantified more precisely by reconstructing historic sediment budgets through the quantification of sediment storage and estimated of sediment transfer in volumes.*

Rather than adopting surrogate measures of sediment quantities, such as widths (m) and areas (m^2) as applied in this study and others (Macklin et al., 1998; Brewer et al., 2000), determining sediment movements in volumes (m^3) provides a more realistic and accurate sediment budget. Similar approaches have attempted on the reach-scale to generated contemporary sediment budgets through detailed levelling (Fuller et al., 2003; Ham and Church, 2000; Brewer and Passmore 2002). To apply this to the historic period will require field determinations of the relationship between bar area and sediment volume within the channel to be calculated for a range of representative channel sections. This will then allow detailed reconstructions of bar areas, measured by digitisation of the entire channel network from historical sources, to be converted to volumes.

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